

Atmospheric composition in the past, present and future: A view from the NASA IR sounders

Topic: Which science questions/topics are essential to address with the 40-year record of IR sounder observations that are currently available or planned for the future?

Vivienne Payne

Jet Propulsion Laboratory, California Institute of Technology

With thanks to:

- JPL/Caltech: Kevin Bowman, Dejian Fu, Jessica Neu, Ming Luo, Elva Kuai, John Worden, Bill Irion, Greg Osterman, Brendan Fisher, Vijay Natraj, Thomas Kurosu, Stan Sander, Mike Gunson
- NASA Ames/BAERI: Susan Kulawik
- AER: Karen Cady-Pereira and colleagues
- Environment Canada: Mark Shephard
- NCAR: Helen Worden, Gene Francis
- Colorado State University: Emily Fischer

- AIRS Science Team
- Suomi-NPP Science Team

- Contributors to the NOAA CrIS atmospheric composition workshop report
- Contributors to the NASA Ames workshop report

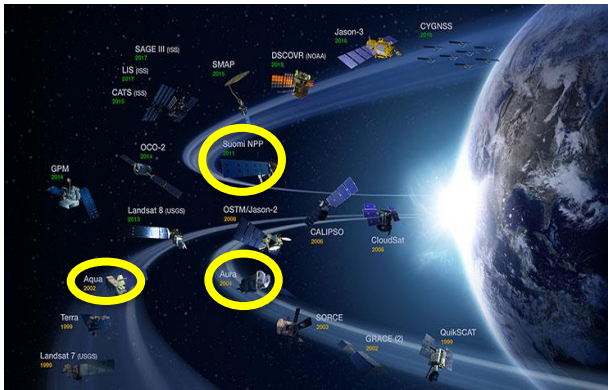
NASA Earth Science Division operating missions



Image from <http://eospso.gsfc.nasa.gov/>

Looking back, looking forward:

- Thermal infrared sounders:
 - Demonstrated radiometric stability
 - Spectrally resolved radiances: Distinct signals from multiple trace gases
- *40-year record of IR sounder observations:*
 - *Opportunity to track and understand changes*



JPSS-1 CrIS: 2017-
JPSS-2 CrIS: 2022-
JPSS-3 CrIS: 2026-
JPSS-4 CrIS: 2031-

Gases responsible for radiative forcing are coupled through common sources & processes within the Earth System.

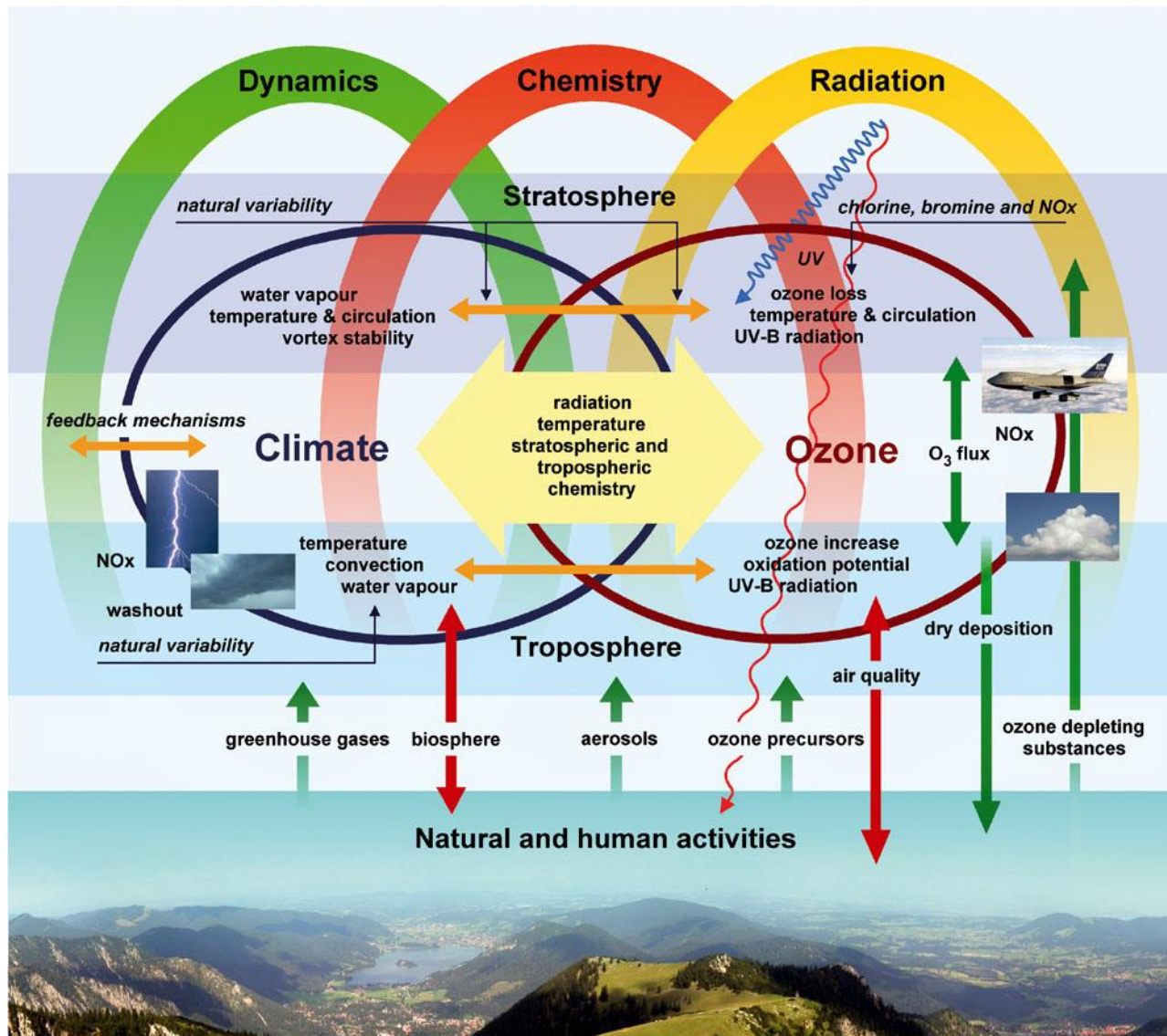


Image: DLR, after WMO-IGACO

Community workshops have provided recommendations

- **2010:** NASA Community Workshop on Polar Orbiting IR and MW sounders
- **2014:** CrIS Atmospheric Chemistry Data User's Workshop Report
- **2014:** NASA Workshop Report on Outstanding Questions in Atmospheric Composition, Chemistry, Dynamics and Radiation for the Coming Decade
- Recommendations include:
 - Formation of a US-based Sounding Team
 - **Continuity** of EOS records
 - **Role of models** in analysis of measurements of atmospheric composition
 - Observations must have **well-characterized errors**
 - **Observation operator** should be supplied for each obs.
 - Observation of **multiple species**, including
 - **O₃, CH₄, NO_x, CO, PAN, NH₃, N₂O, HNO₃, VOCs**

Critical questions (tropospheric gases)

(adapted from NASA SMD 2014 Workshop report)

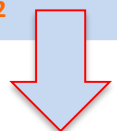
- How are emissions changing spatially and temporally and how is composition (e.g. tropospheric ozone) responding?
- How are volatile organic compounds (VOCs) oxidized in the atmosphere, and how can the impacts on composition be represented in models?
- How are humans and climate perturbing the nitrogen cycle?
- What is responsible for methane emissions and their trends?
- How does convection redistribute trace constituents in the troposphere?

Available trace gas products from **NASA/NOAA** thermal-IR sounders*

Omnipresent

Observable at enhanced concentrations

Molecule	AIRS v6	AIRS OE J. Warner et al	AIRS NUCAPS	TES v7	CrIS NUCAPS	CrIS AER/NCAR ⁺
O ₃	Y		Y	Y	Y	
O3 IRKs				Y		
CO	Y	Y	Y	Y	Y	+
CH ₄	Y		Y	Y	Y	
CO ₂	Y		Y	Y	Y	
N ₂ O		Y	Y	Y	Y	
HDO				Y		
HNO ₃		Y	Y		Y	
OCS	AIRS gap	AIRS gap	AIRS gap	Y	CrIS gap	CrIS gap
NH ₃		Y		Y		+
CH ₃ OH				Y		
HCOOH	AIRS gap	AIRS gap	AIRS gap	Y	CrIS gap	CrIS gap
PAN				Y		
SO ₂	flag		Y		Y	



* Attempt to capture range of products avail – please excuse omissions/misunderstandings
 + Not yet publicly available, but will be in foreseeable future

Scientific utilization of trace gas products

- Sensitivity of the measured radiances to any given trace gas depends on
 - Instrument characteristics (spectral resolution, noise)
 - Details of the surface and atmospheric state
- Required for meaningful quantitative interpretation of remotely-sensed products:
 - Sensitivity diagnostics (i.e. averaging kernels)
 - Well-characterized error estimates
 - Required on a case-by-case basis
- Optimal estimation retrievals provide a means to supply these

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Tropospheric Ozone is the Third Most Important Greenhouse Gas and an Air Pollutant



Ozone affects air-quality and plant health

Ozone is a greenhouse gas in the mid- and upper troposphere

Reduced CO₂ uptake from damaged plants also strongly affects climate

Ozone: The New Standard



United States Environmental Protection Agency

EPA Strengthens Ozone Standards to Protect Public Health/Science-based standards to reduce sick days, asthma attacks, emergency room visits, greatly outweigh costs

Release Date: 10/1/2015

Contact Information: Enesta Jones, Jones.enesta@epa.gov, 202-564-7873, 202-564-4355; En español: Lina Younes, younes.lina@epa.gov, 202-564-9924, 202-564-4355

“Based on extensive scientific evidence on effects that ground-level ozone pollution, or smog, has on public health and welfare, the U.S. Environmental Protection Agency (EPA) has strengthened the National Ambient Air Quality Standards (NAAQS) for ground-level ozone to 70 parts per billion (ppb) from 75 ppb to protect public health.”

Future standards?



American Lung Association Responds to EPA Ozone Standard Update, Impact on Public Health

(October 1, 2015) - Washington, DC Today, in response to the updated National Ambient Air Quality Standards for ozone announced by the Obama Administration, Harold P. Wimmer, National President and CEO of the American Lung Association, issued the following statement:

For more information please contact

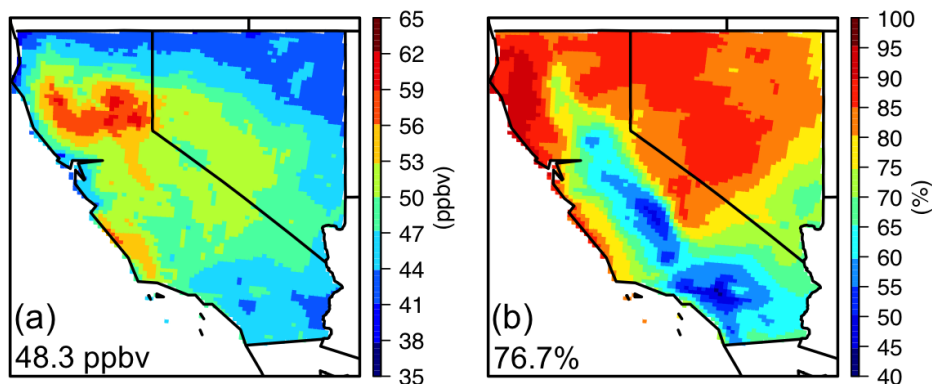
Allison MacMunn
media@lung.org
(312) 801-7628

The EPA's independent scientific advisors reviewed the evidence and concluded that a level of 60 ppb would provide more public health protection than a standard of 70 ppb. Furthermore, leading medical and health organizations and more than 1,000 health and medical professionals continuously voiced strong support for a standard at 60 ppb.

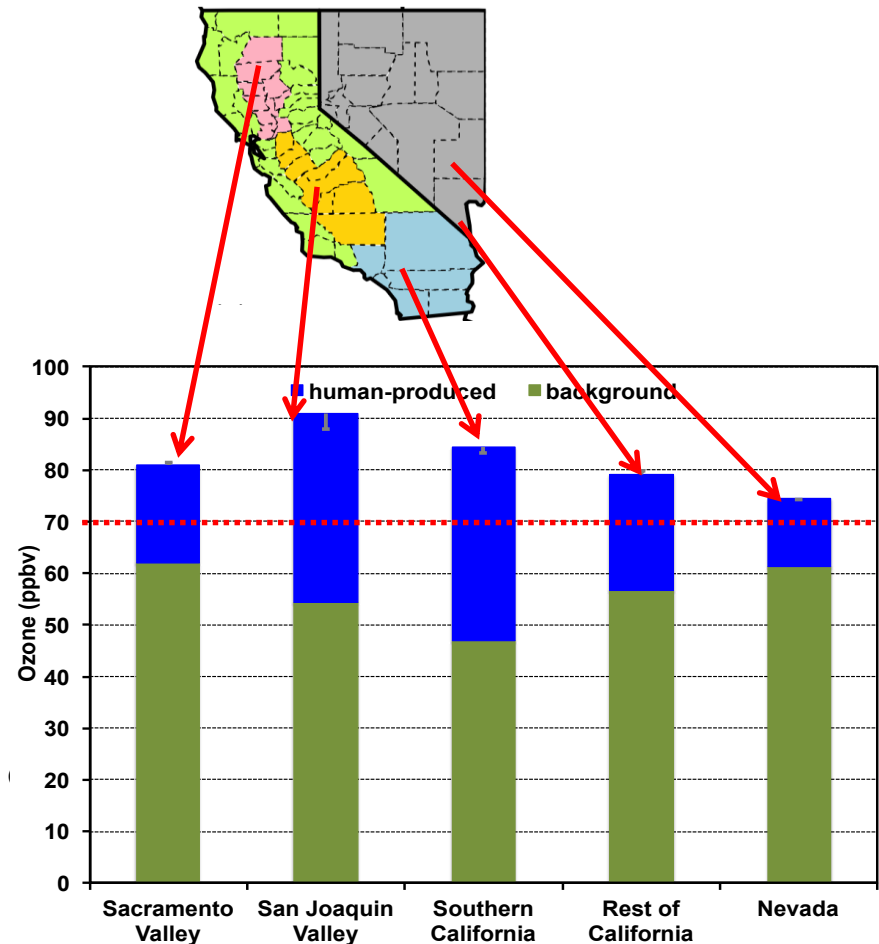
Attribution of background ozone and local sources

Huang et al. (2015) assimilated TES ozone and OMI NO₂ in a multi-scale assimilation system, which improves the model skill relative to independent measurements.

Increases in non-local pollution and local wildfires will require additional reductions in local anthropogenic emissions to meet standards.



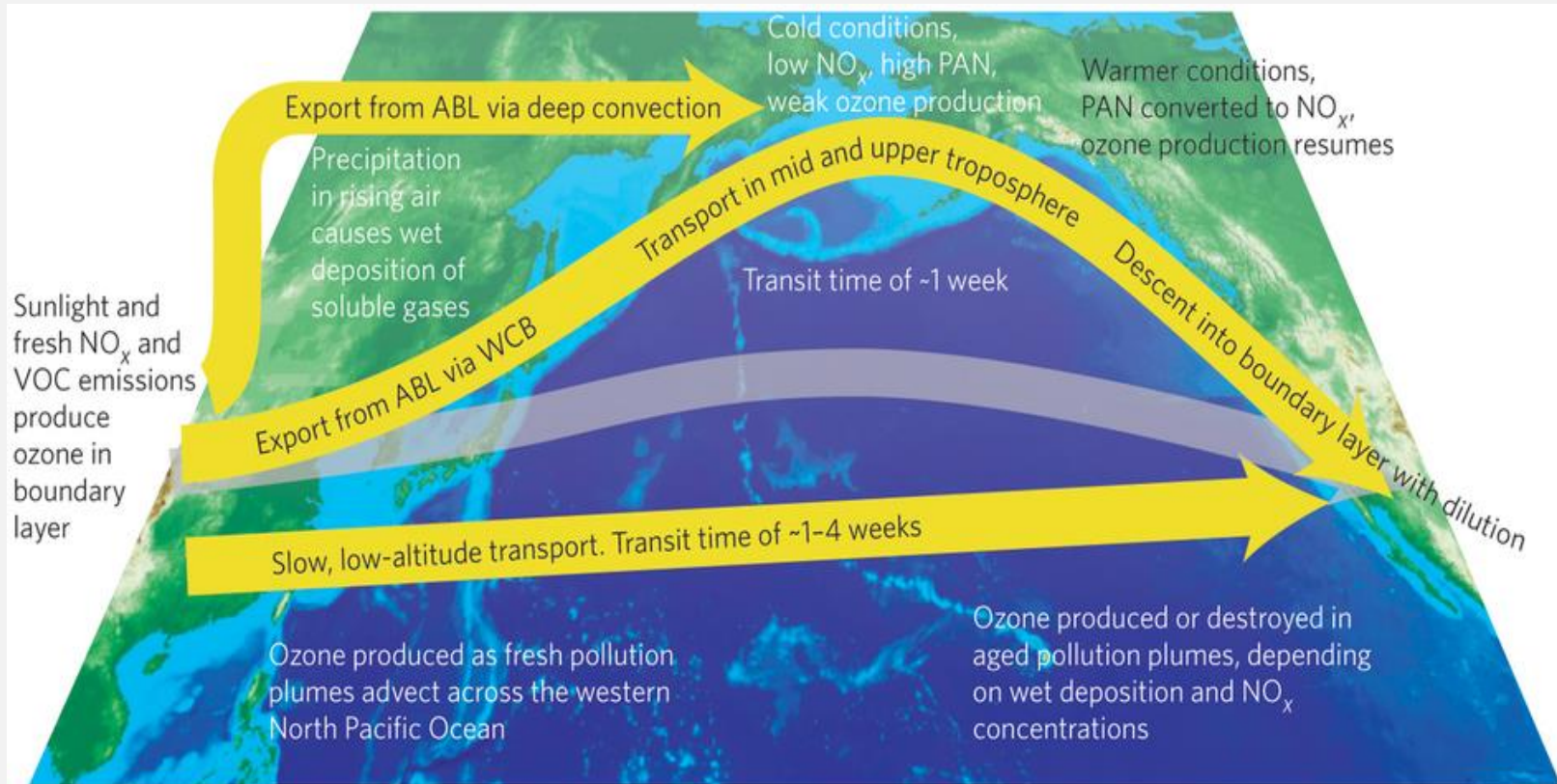
Mean Background Ozone and its Contribution to Total Surface Ozone as Constrained by TES and OMI



Proposed reductions in the EPA primary ozone standard increase the importance of accurate attribution of background (non-local and local natural) and local human ozone sources.

Natural variability vs changes in emissions

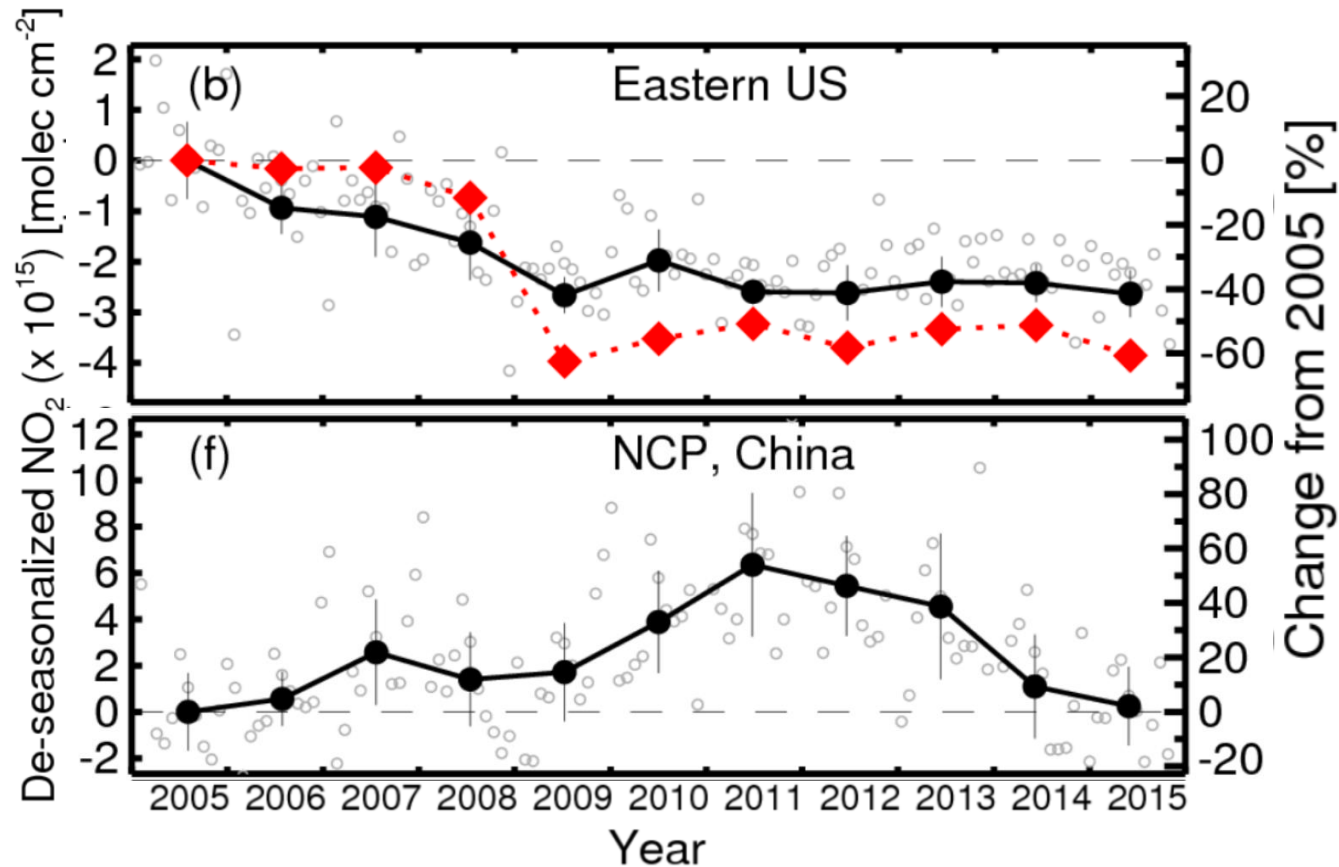
Verstraeten et al., Nature Geosci., 2015: Combine Aura meas (MLS, TES, OMI) with a model to quantify and attribute observed changes in ozone over the Western US from 2005-2010



Natural stratospheric variability played a surprisingly large role in tropospheric ozone trends in the Western US. Chinese emissions offset a large portion of the reduction in mid-tropospheric ozone that would otherwise have occurred. The absolute impact of Chinese emissions has thus far been small, but its future trajectory is highly uncertain.

Relative changes in OMI NO₂ [Krotkov et al. [2016]]

What will global shifts in emissions look like in the future, and what will be the impacts of emissions on atmospheric composition?

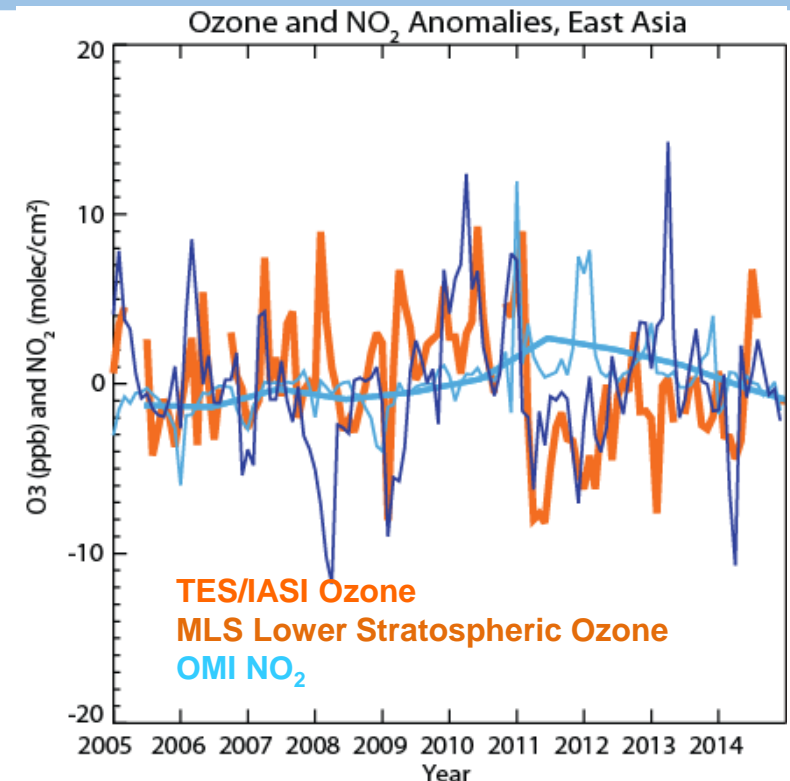
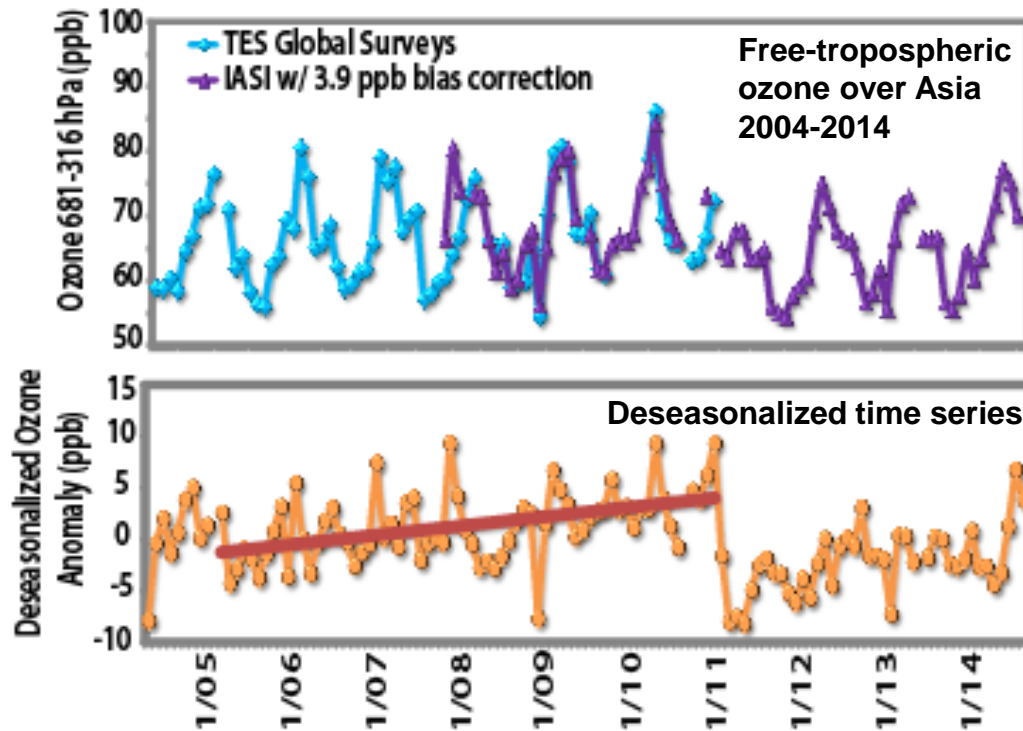


Long-term tropospheric ozone record from TES and IASI



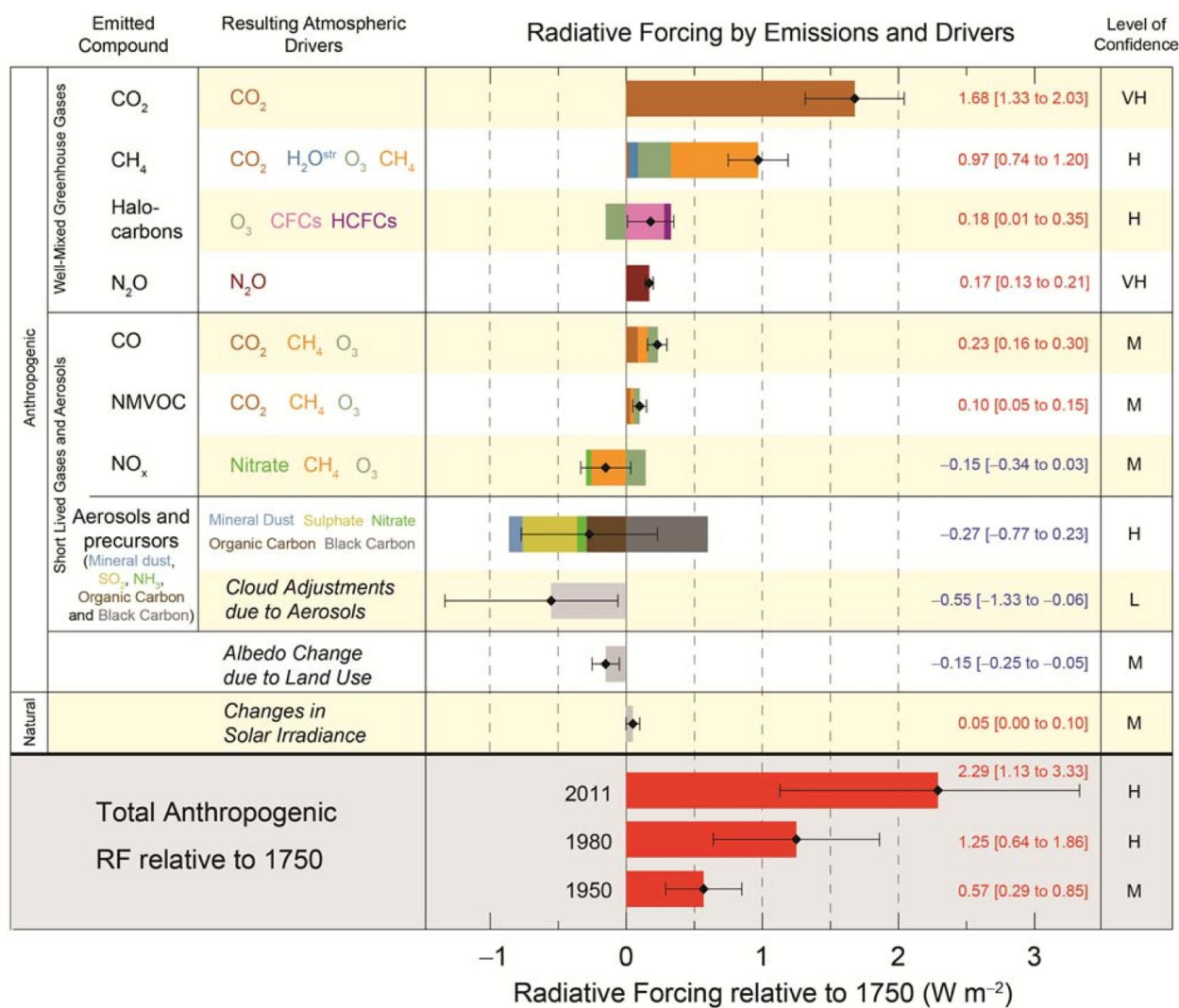
Joint TES/IASI record of tropospheric ozone over East Asia shows that contrary to expectations, rapid increases observed between 2004 and 2010 do not continue after 2010. *Oetjen et al., ACP (2016)*

NO_x emissions from Eastern China appear to decrease after 2011 – what are the relative roles of emissions decreases and stratospheric variability?



Level of confidence in radiative forcing

IPCC AR5



Well-mixed greenhouse gases are associated with high level of confidence. “Short-lived” components, not so much.

Radiative forcing due to tropospheric ozone is highly variable spatially

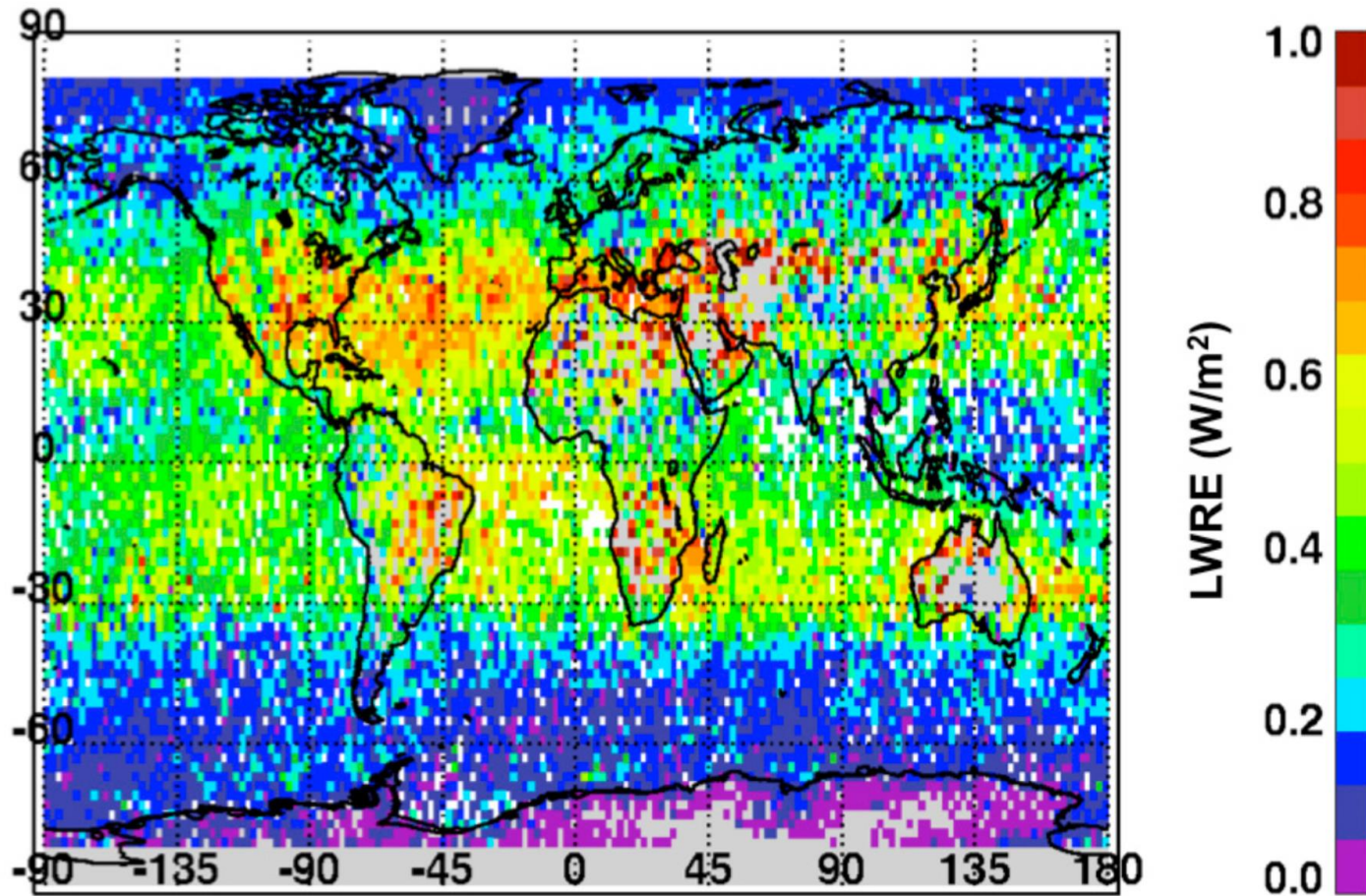
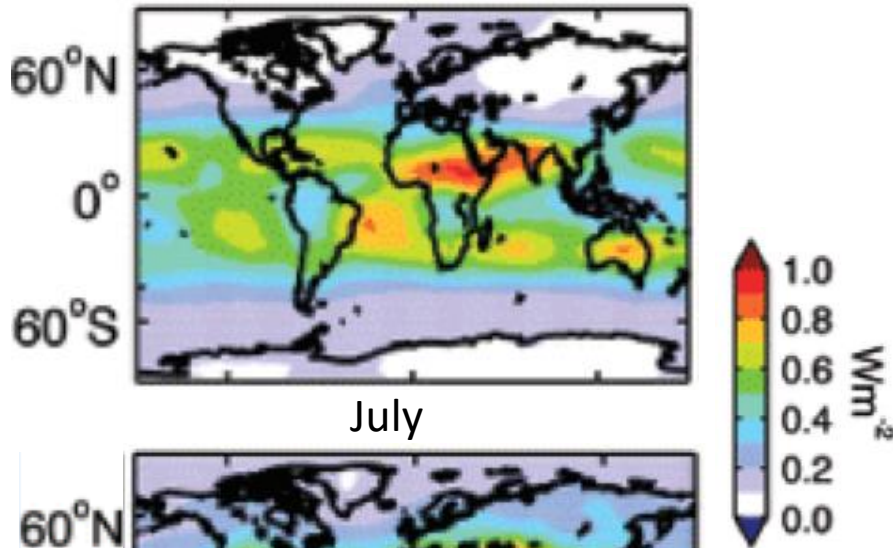


Figure: Longwave radiative effect due to ozone [Worden et al., 2011]

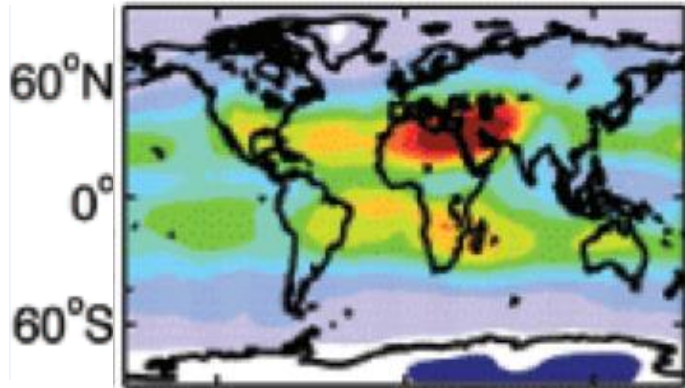
Spatial distribution of ozone precursor emissions matters [Bowman and Henze, 2012]

Hydrological controls on the tropospheric ozone greenhouse gas effect (Kuai et al., 2017)

January



July



The greenhouse effect due to tropospheric ozone, or longwave radiative effect (LWRE), as measured by Aura TES, for January and July 2006.

Magnitude of the greenhouse effect due to O_3 depends on distribution of:

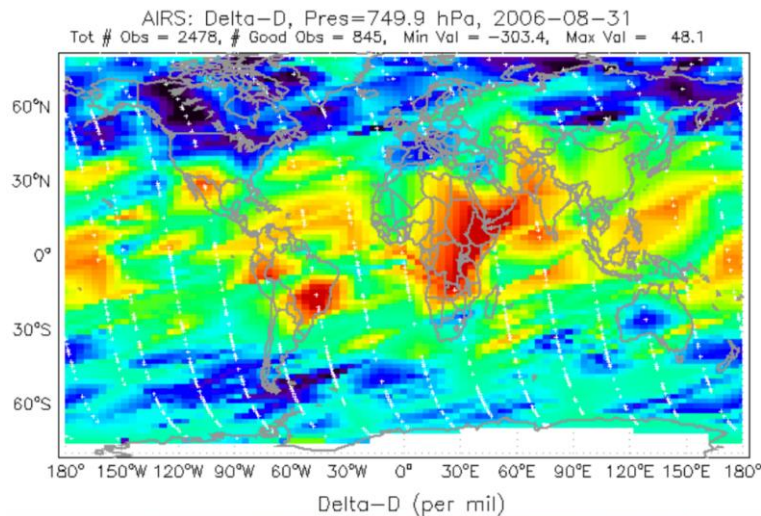
- O_3
- **Water vapor/relative humidity**
- **Surface temperature**
- **Clouds**

Strongest effect over Middle East in July (low water, high surface temperature)

Stronger effect in sub-tropics than in tropics (lower water vapor, less cloud)

Changes in the hydrological cycle due to changes in large-scale circulation (e.g. Hadley cell expansion) could affect the ozone radiative forcing.

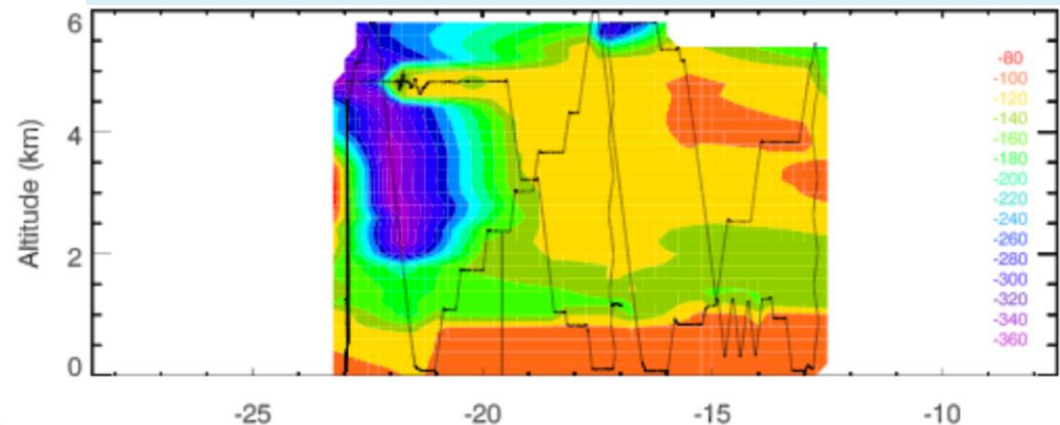
Hydrological cycle: AIRS retrievals of HDO



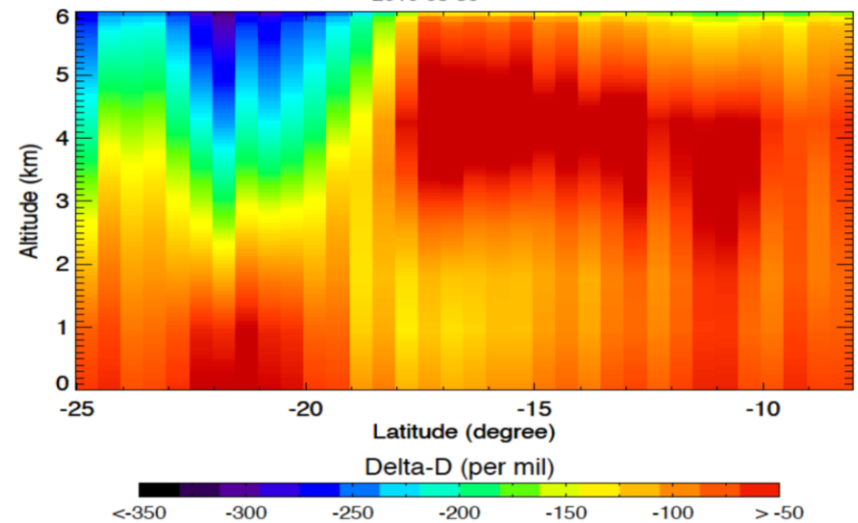
- HDO measurements from TES have been used to place constraints on the hydrological cycle.
- Strow et al.: Previous work demonstrating feasibility of AIRS HDO using shortwave channels

AIRS HDO from mid-wave channels:
See Herman et al. poster at
A-train Symposium!

Initial comparisons with data from ORACLES aircraft campaign
(Southeast Atlantic)

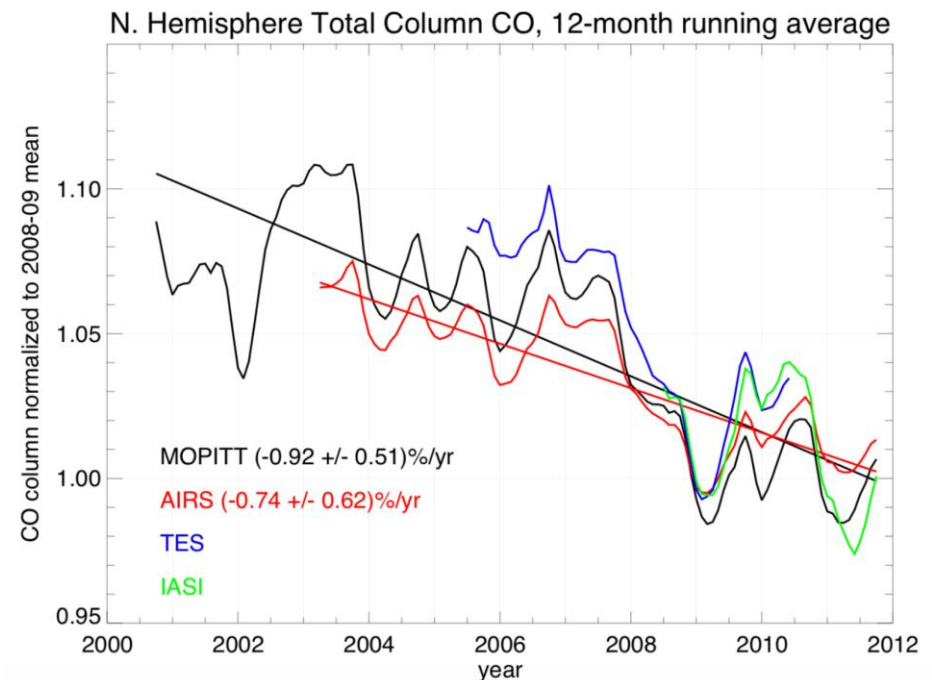
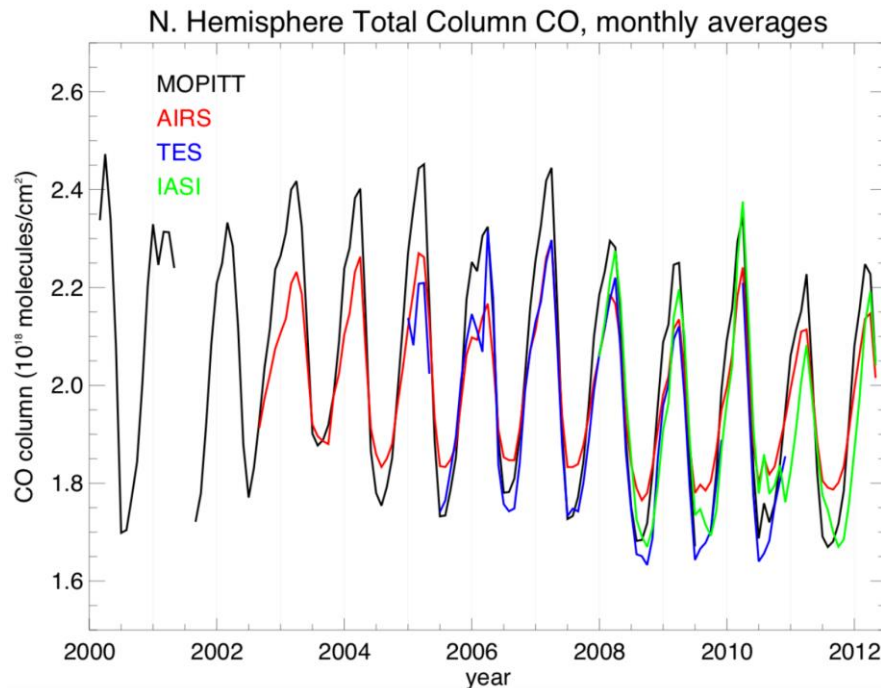


AIRS: Delta-D, near "Offshore", along track within 500KM
2016-08-30



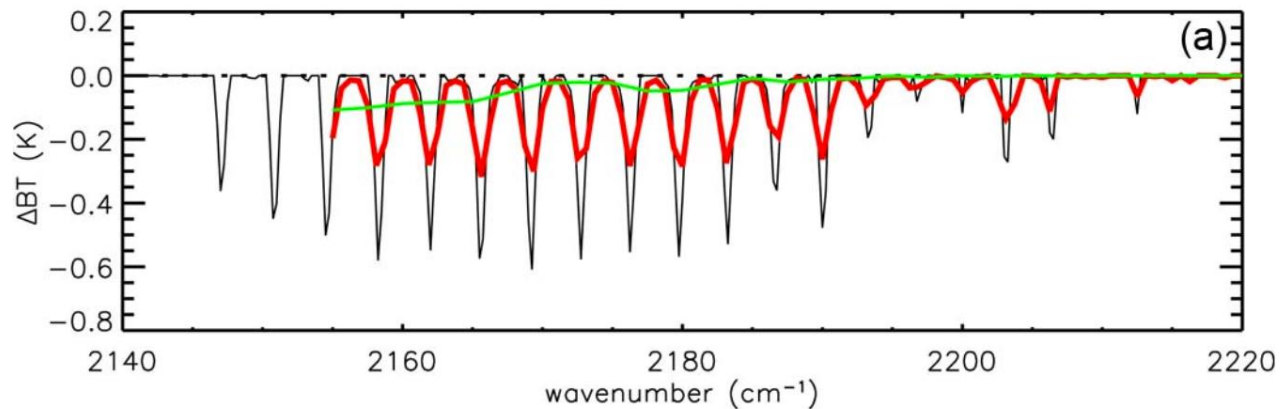
Carbon monoxide

- Sources: Product of incomplete combustion, Oxidation of hydrocarbons
- Plays a key role in atmospheric chemistry
 - Main sink for hydroxyl radical (OH)
 - Important precursor for tropospheric ozone
- How will emissions and concentrations change in future and what are the implications for tropospheric ozone?



Figures from Worden et al. [2013], showing interannual variability and overall decreasing trend in NH CO (MOPITT is TIR only in these figures.)

Carbon monoxide from CrIS high resolution spectra

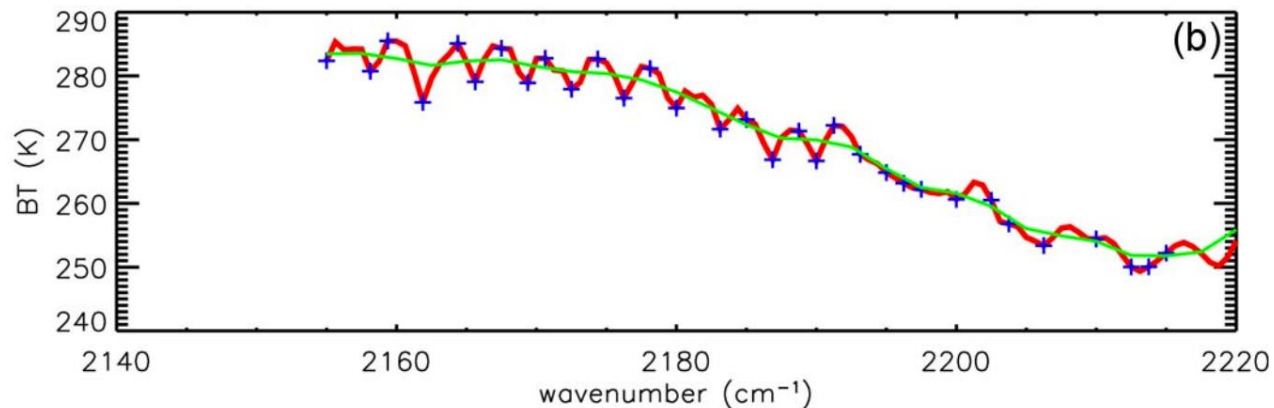


Sensitivity to 1 % perturbation in CO:

2.5 cm^{-1}

0.625 cm^{-1}

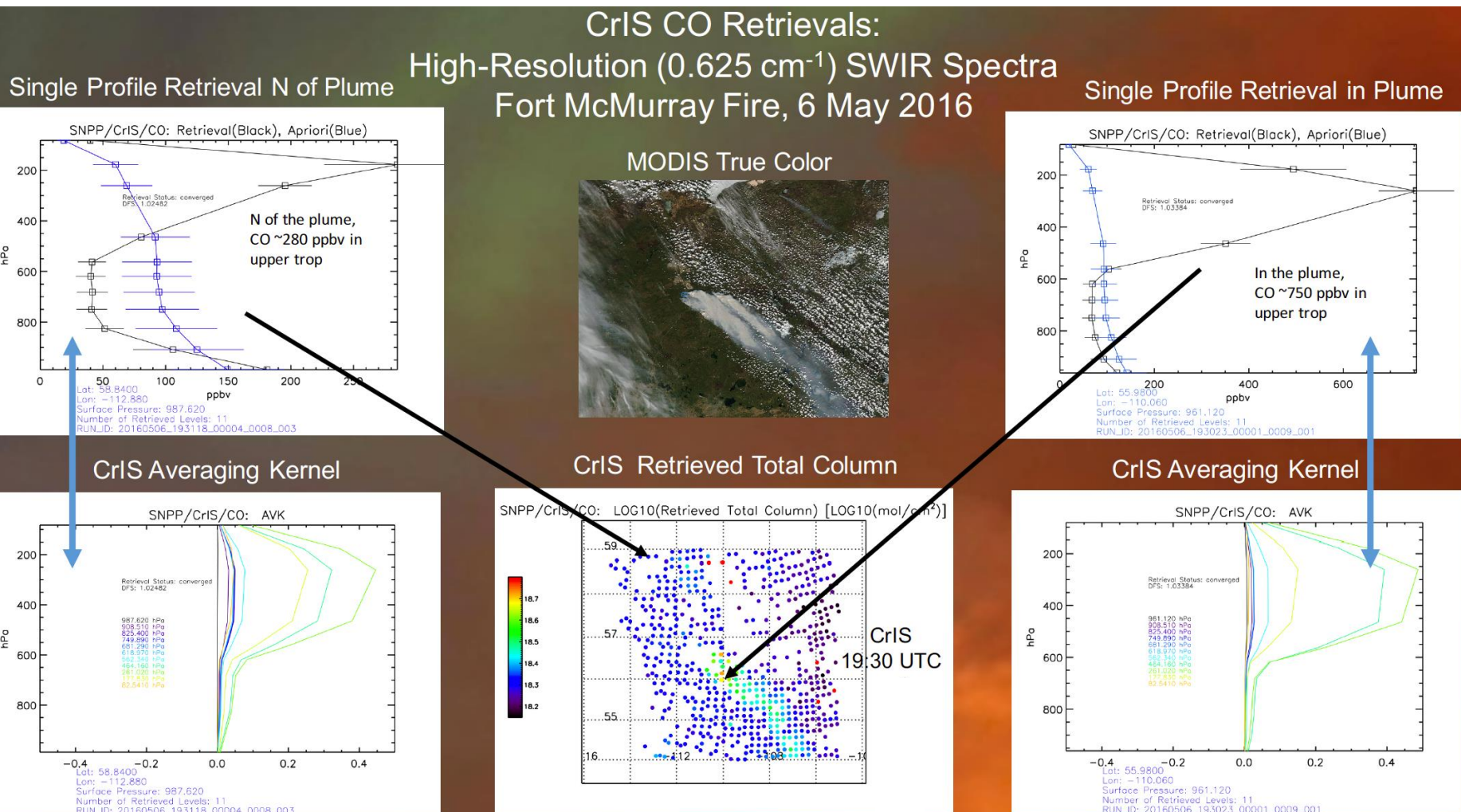
0.25- cm^{-1}



Comparison of low and high spectral resolution CrIS measurements

- Figure: Gambacorta et al. [2014]

Extending the TIR CO record from CrIS



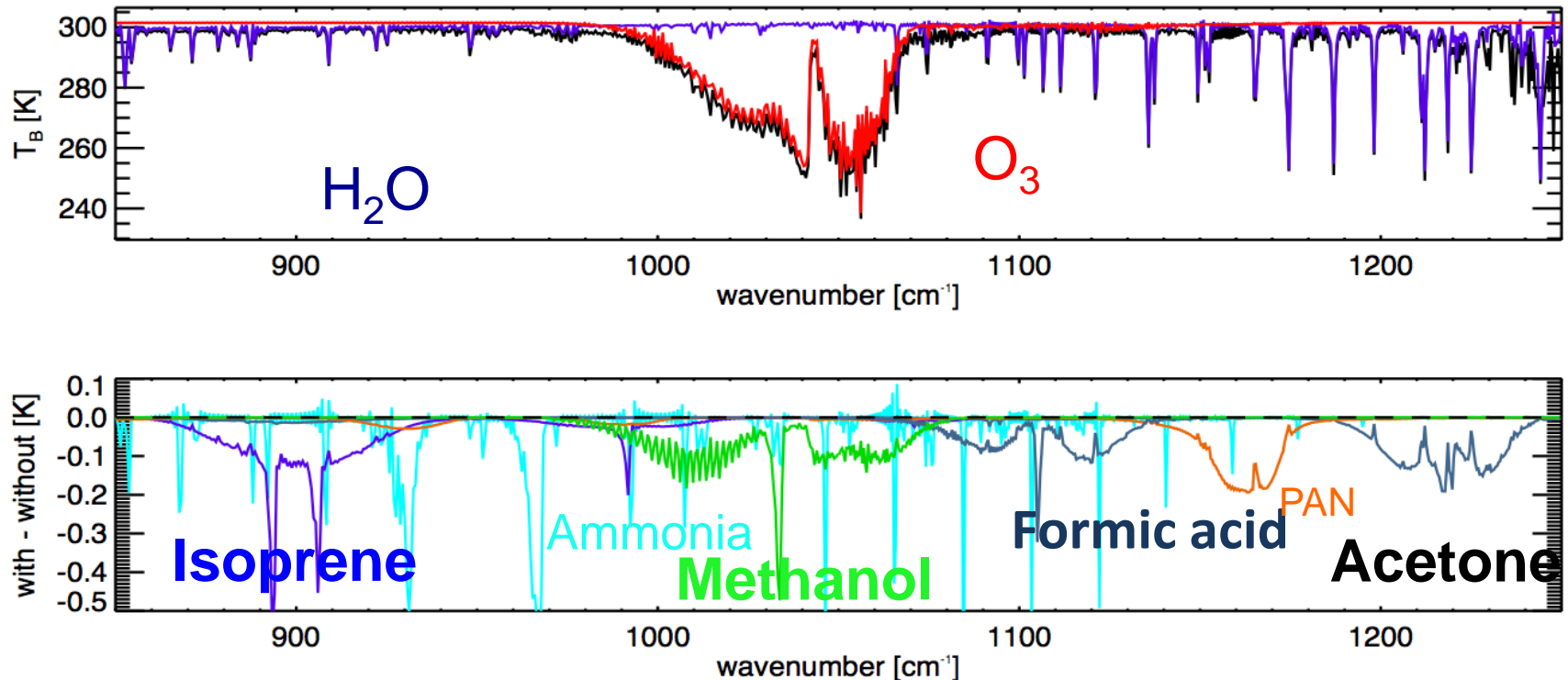
Francis et al., "Toward a Multi-Decadal Record of Satellite CO from MOPITT to Suomi NPP/CrIS",
Presented at 2016 AGU Fall Meeting

Critical questions (tropospheric gases)

(adapted from NASA SMD 2014 Workshop report)

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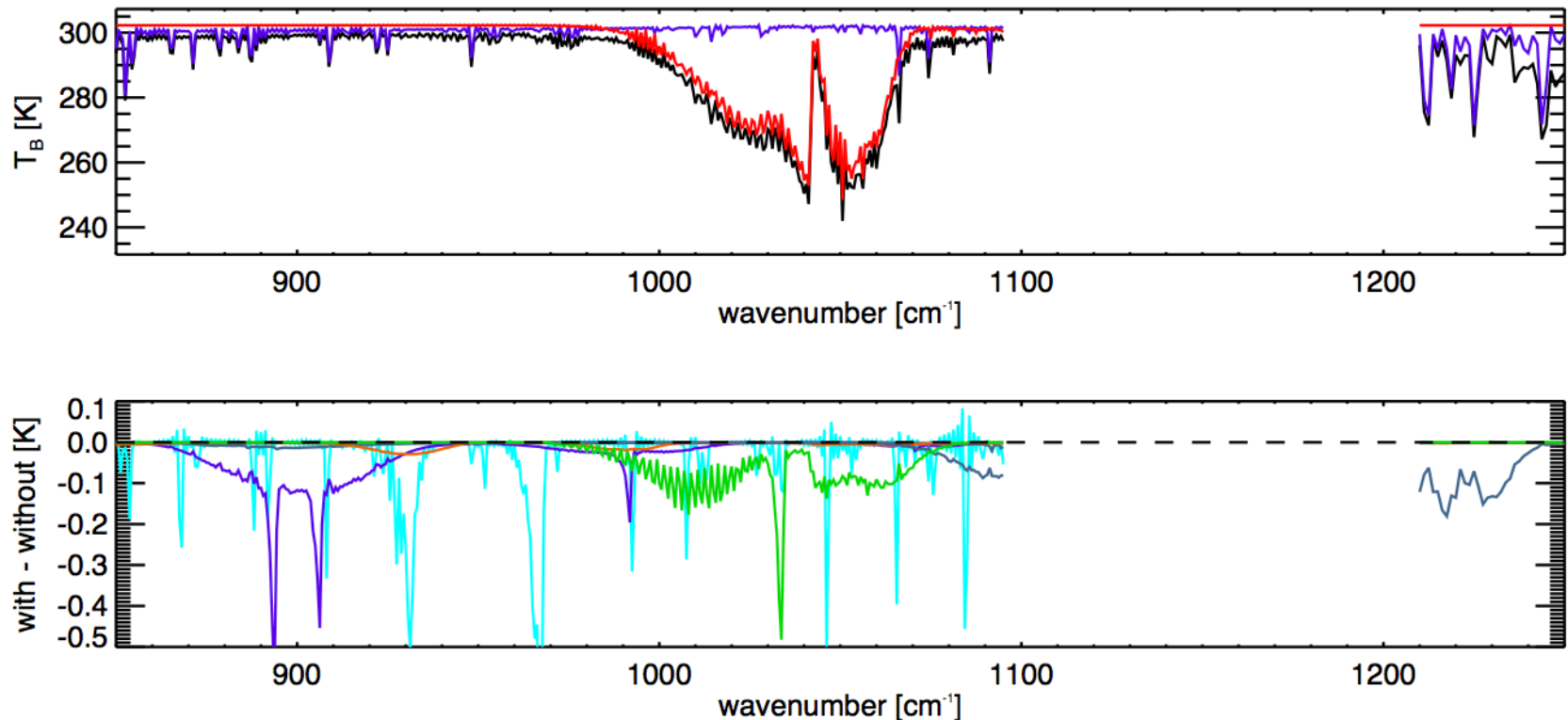
IR sounders offer information on biogenic volatile organic compounds (VOCs)



Isoprene retrievals from CrIS (**Fu et al.**)

Combine CrIS isoprene Aura OMI (HCHO , NO_2) and the GEOS-Chem model to advance understanding of isoprene oxidation and HCHO production across NO_x regimes.
(**Millet et al.**)

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Peroxyacetyl Nitrate (PAN)

- PAN: Reservoir for NO_x radicals, Important for **long-range transport of pollution**
- Sources: **Anthropogenic NO_x** , **fire NO_x** , **lightning NO_x** in the presence of biogenic VOCs
- Represents a significant fraction of the reactive nitrogen budget
- Challenging to represent well in models
- Studies utilizing PAN from TES:
 - Payne et al. [2014]; Zhu et al. [2015]; Payne et al. [2015]; Jiang et al., [2016]; Zhu et al., [2016]; Fischer et al. [2016]
- **TES PAN retrievals use feature at $1140\text{--}1180\text{ cm}^{-1}$** (falls in AIRS/CrIS spectral gap)
- For **AIRS/CrIS**: Use feature at **$780\text{--}810\text{ cm}^{-1}$**

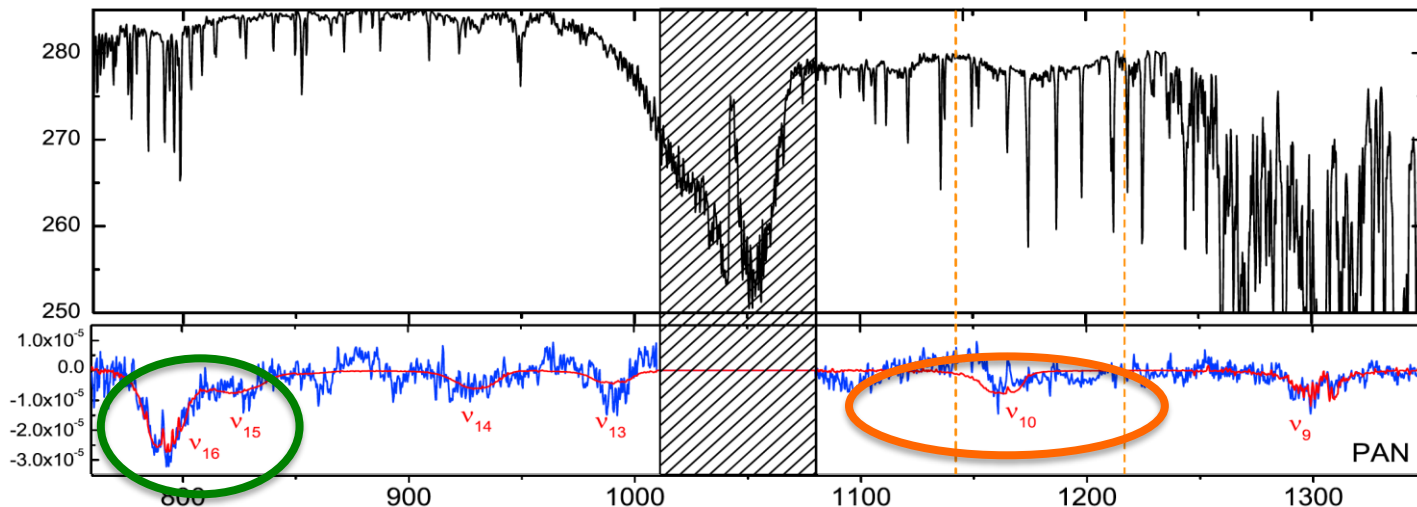
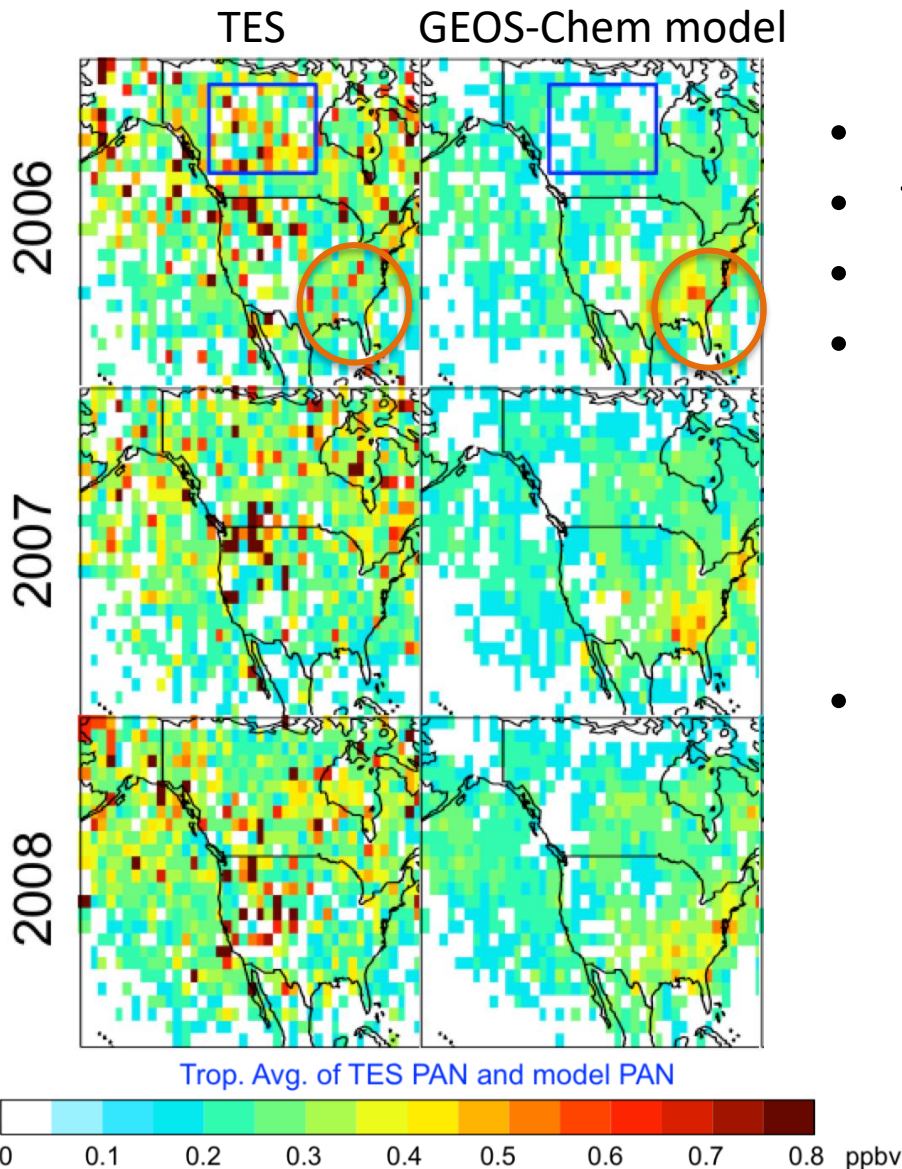


Figure from Clarisse et al. [2011]

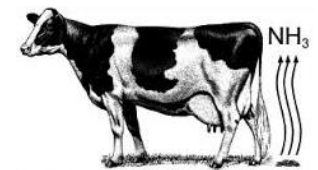
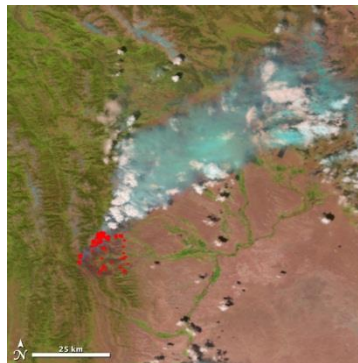
Comparisons between TES and GEOS-Chem



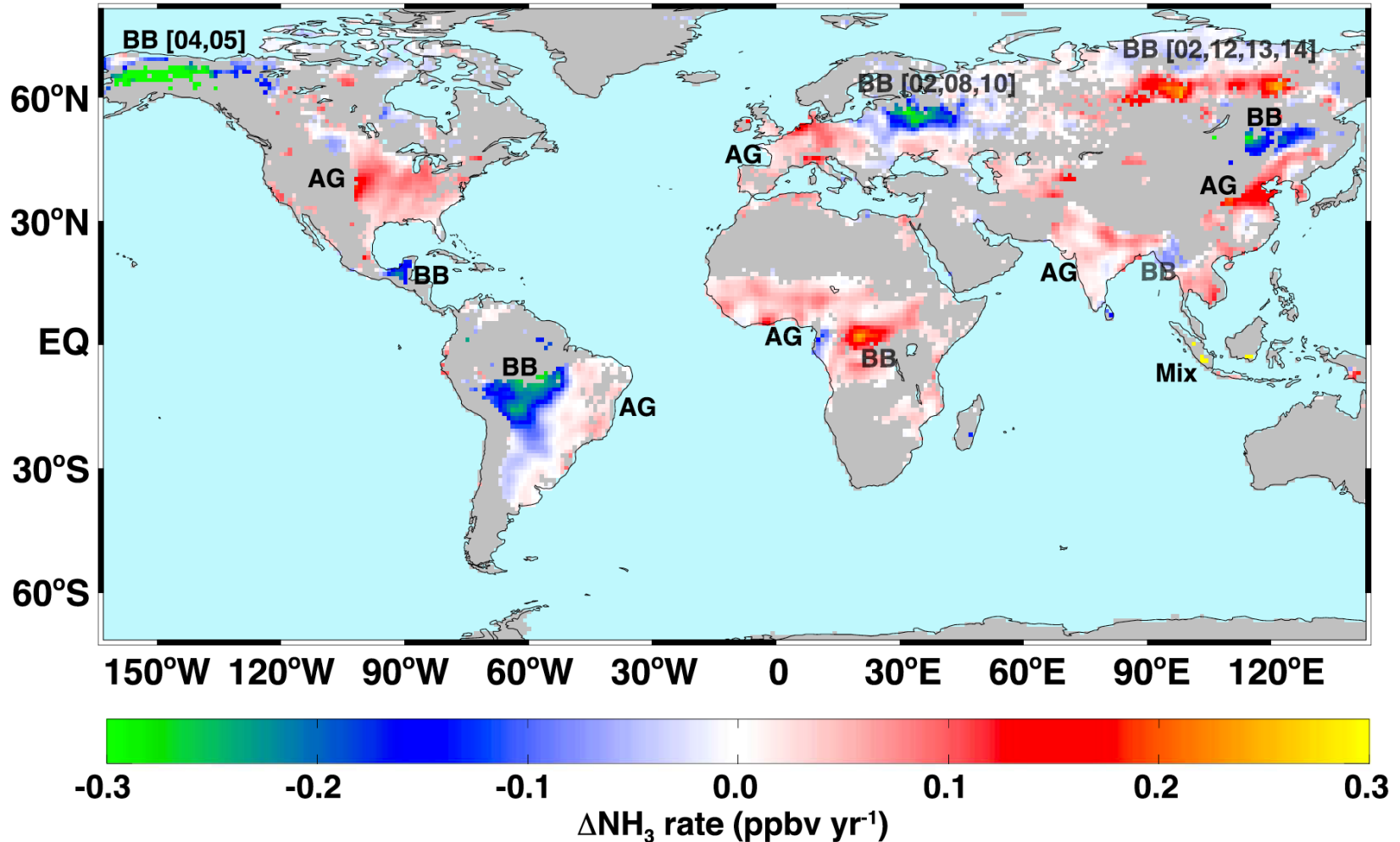
- Fischer et al. [2017], in prep
- TES data from July of multiple years
- Model **underestimates PAN from fires**
- Model overestimates PAN in South Eastern US
 - Addressed by reducing **NOx emissions** and updating **isoprene chemistry**
 - Consistency with independent study using aircraft meas [Travis et al., 2016]
- PAN from CrIS and AIRS:
 - Extension of record (better assess interannual variability)
 - Enhanced spatial coverage

Ammonia (NH₃)

- NH₃ is a major pollutant in both the developed and the developing world
- NH₃, SO₂ and NO_x are key PM_{2.5} precursors
- Impacts on human health:
 - Increase incidence of cardiovascular and respiratory diseases
- In the United States:
 - SO₂, NO_x emissions decreasing due to controls
 - NH₃ is increasing and not subject to controls



14 years of NH_3 from AIRS [Warner et al., 2017]



How will changes in agricultural practices affect NH_3 concentrations in future?
How will changes in fires affect NH_3 concentrations in future?

AER/NCAR CrIS NH₃ product (heritage in TES OE algorithm)

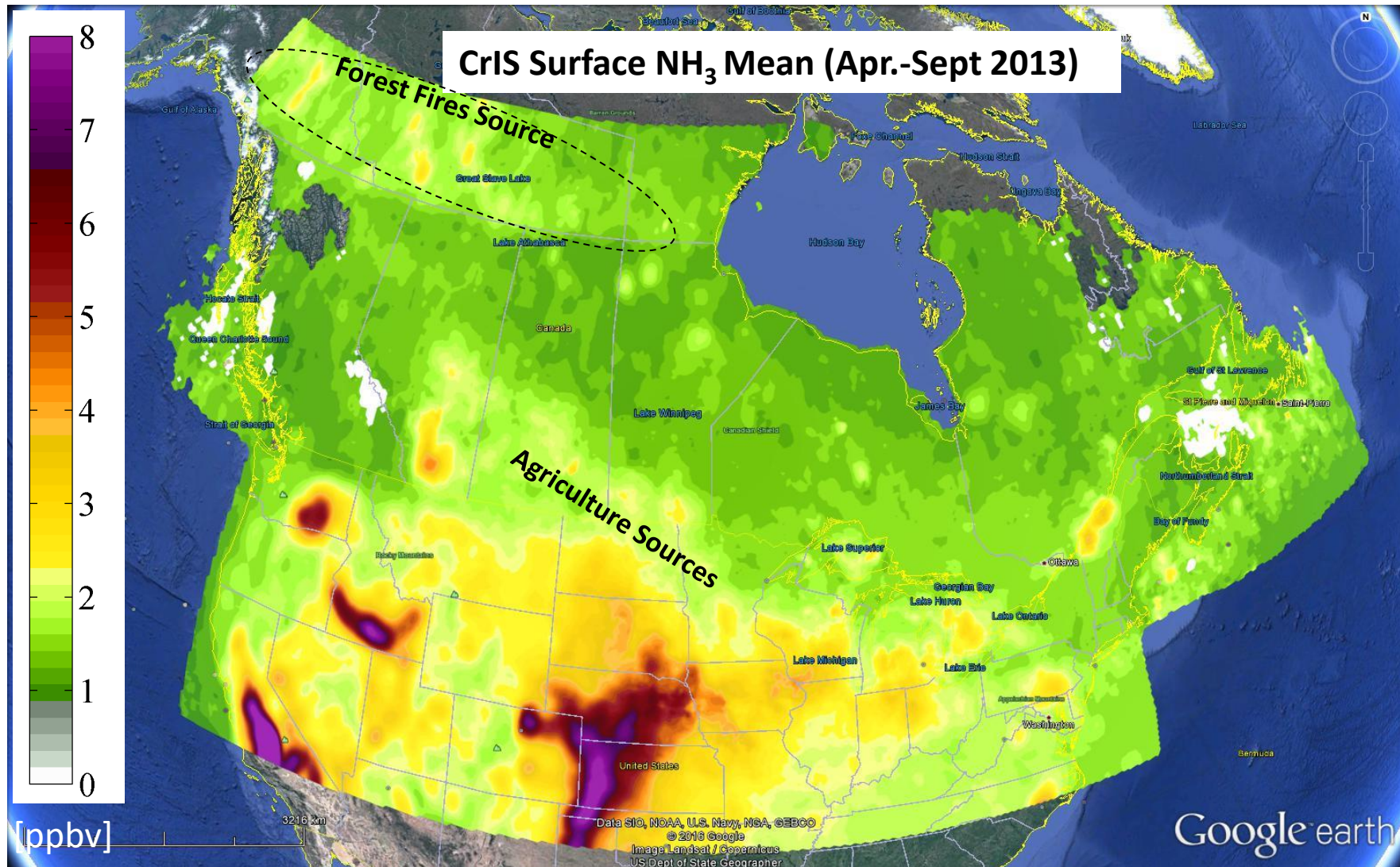


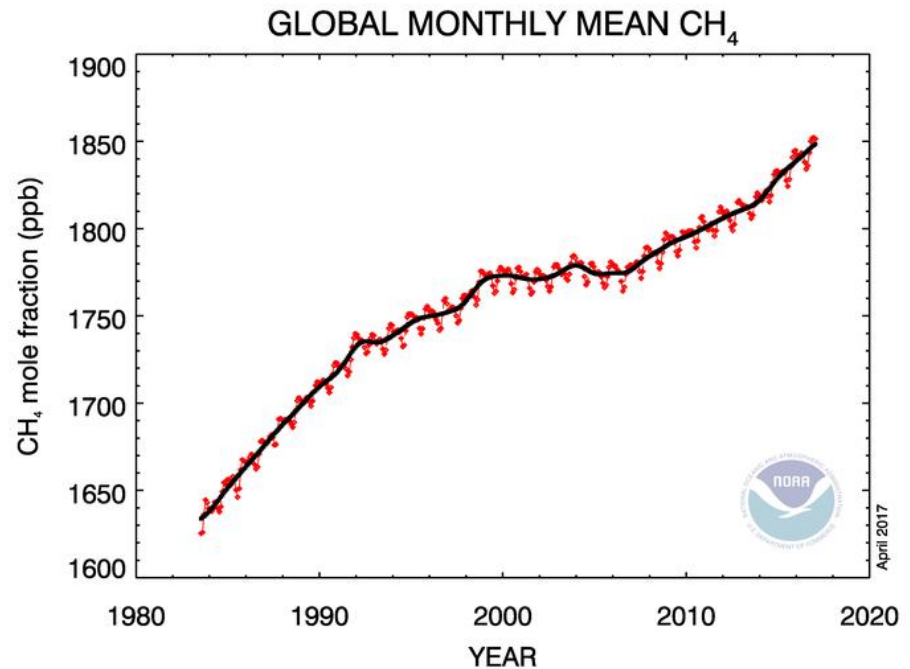
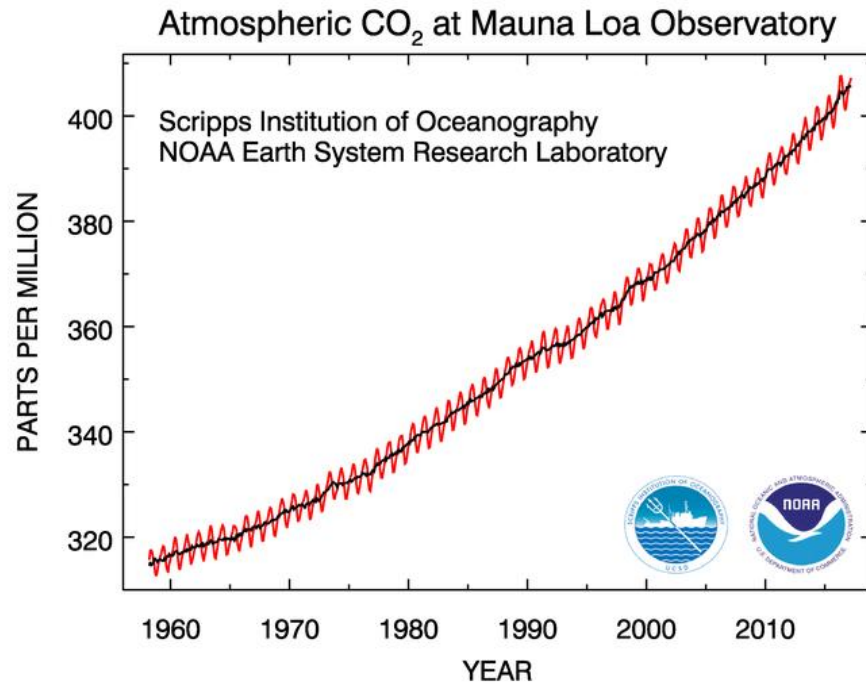
Figure: Mark Shephard (EC), Karen Cady-Pereira (AER)

Critical questions (tropospheric gases)

(adapted from NASA SMD 2014 Workshop report)

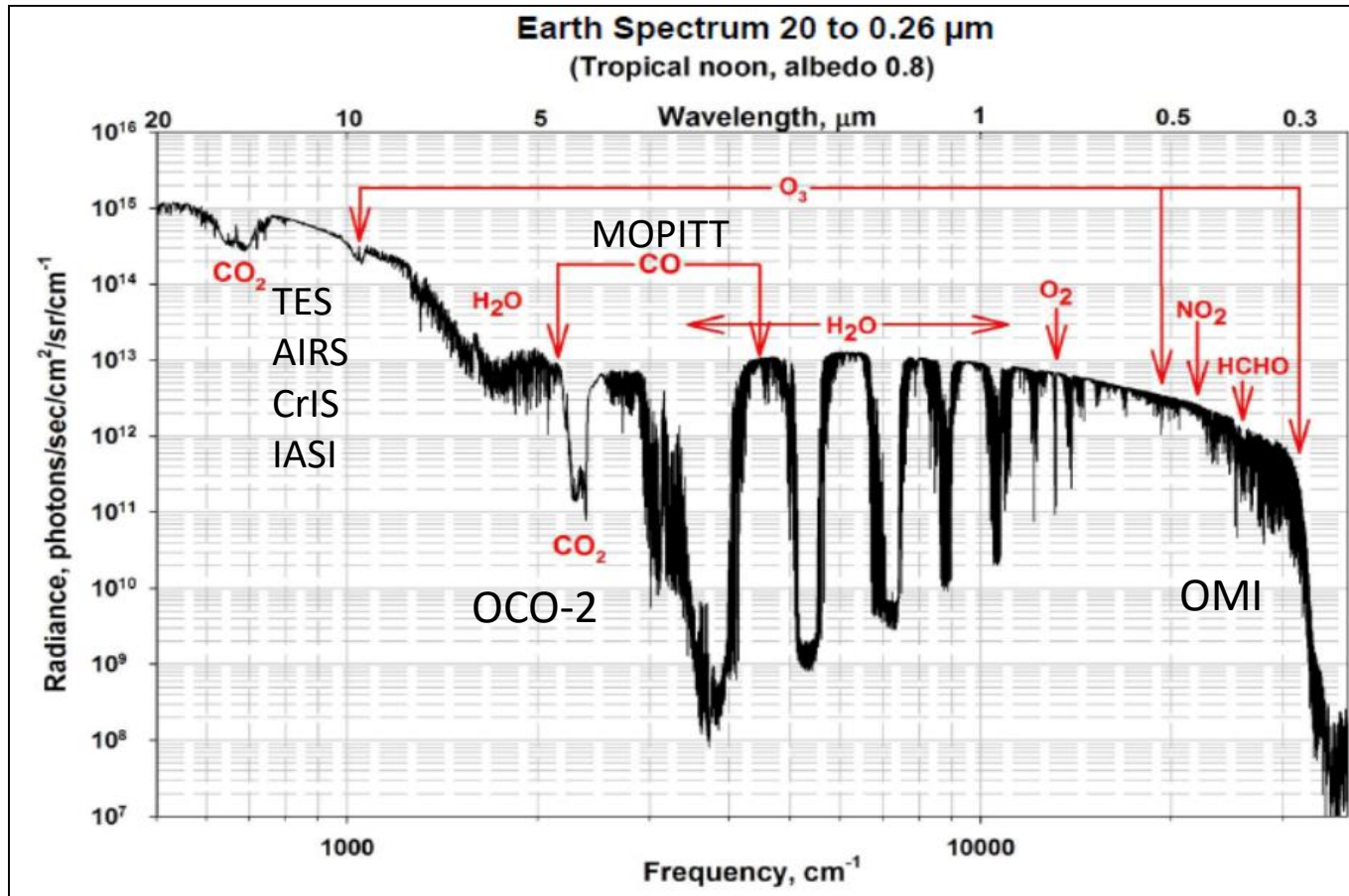
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Growth rate and future distribution of CO_2 and CH_4 are subject to large uncertainties



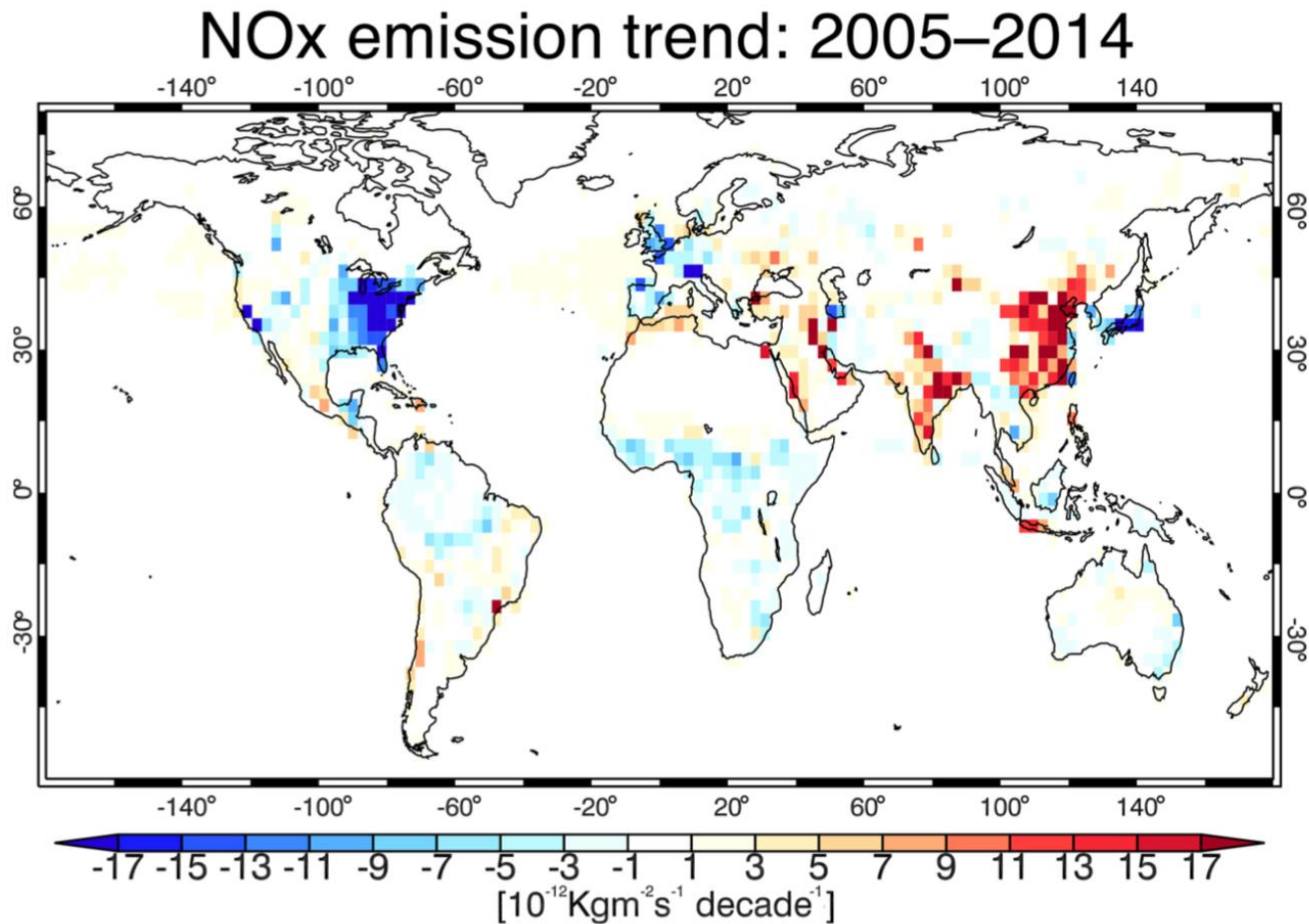
How do the growth rates and future distributions of greenhouse gases depend on natural and anthropogenic factors?

Remote sensing: quantum mechanics in action



Science return of thermal infrared sounder measurements can be enhanced by consideration of other spectral regions

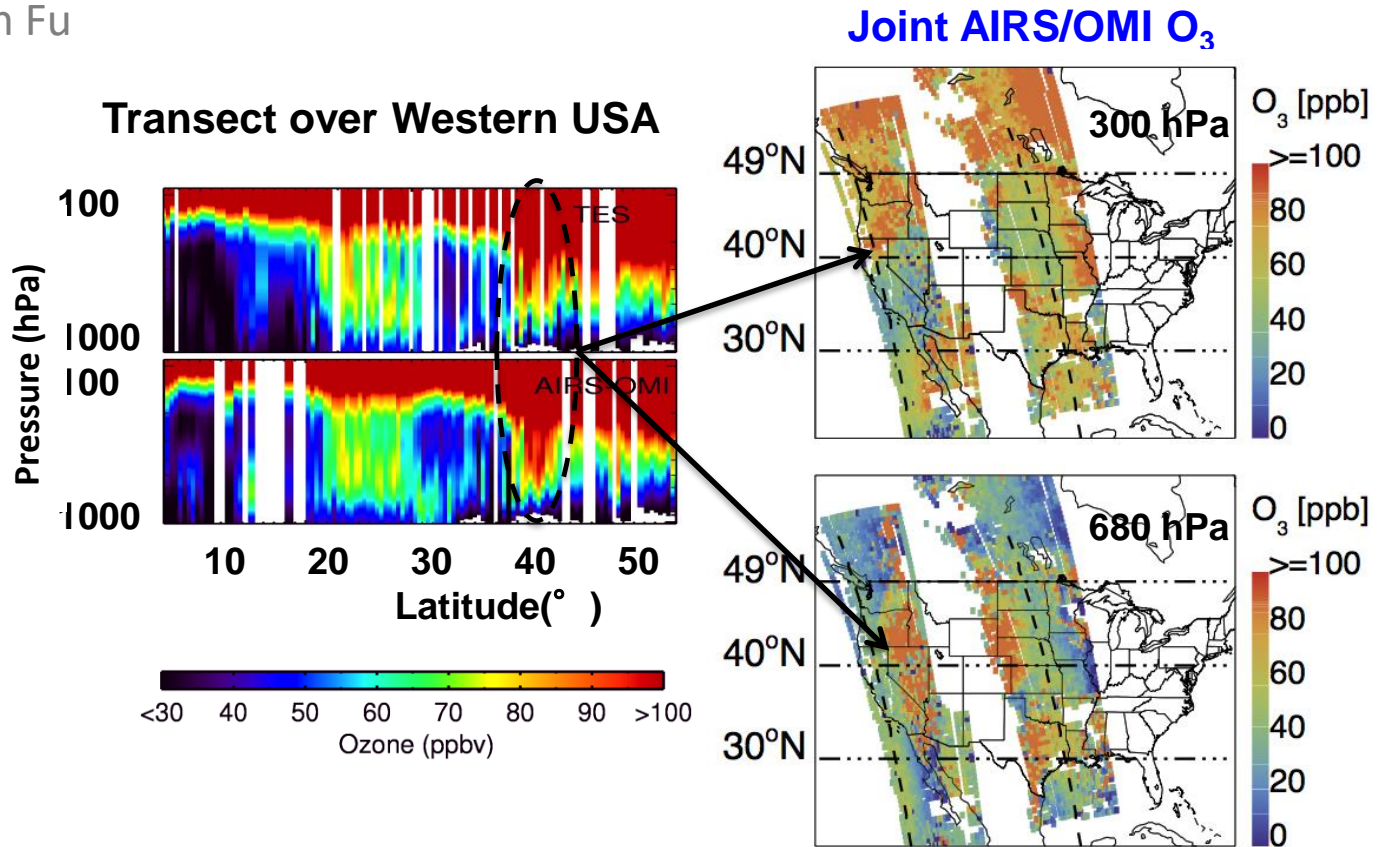
Optimization of multiple species concentrations simultaneously with emissions mitigates issues with model chemistry
(Miyazaki et al., 2017)



Assimilation of multiple satellite data sets: NO₂ from OMI, GOME-2 and SCIAMACHY, O₃ from TES, CO from MOPITT, and O₃ and HNO₃ from MLS using an ensemble Kalman filter technique. Chemical concentrations of various species and emission sources of several precursors were simultaneously optimized.

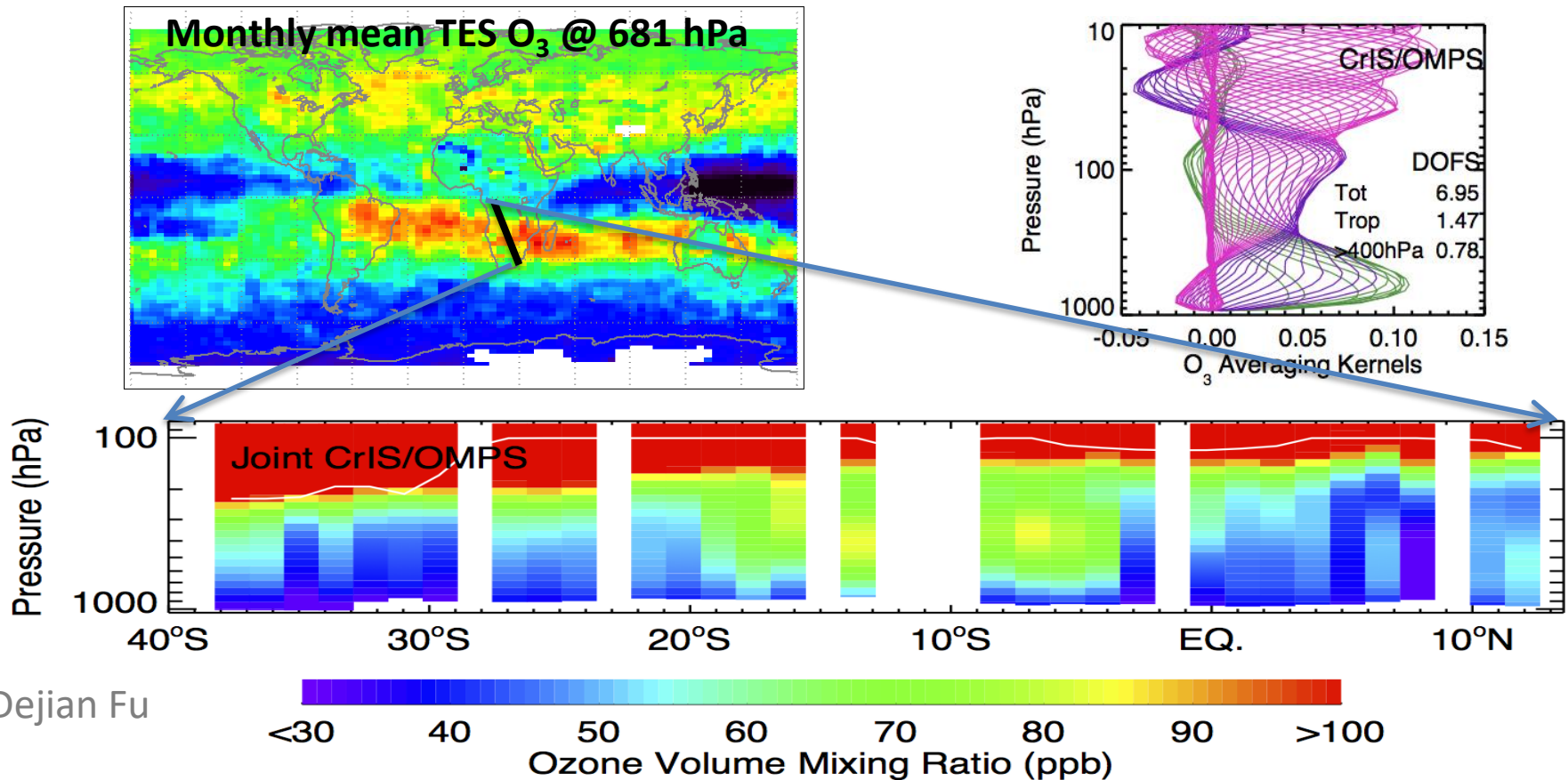
Multi-satellite, multi-spectral retrievals: AIRS/OMI O₃

Figures: Dejian Fu



AIRS/OMI O₃ product offers vertically-resolved tropospheric O₃ with swath coverage
Example from TexAQS (August 2006) demonstrates part of planned support for the NOAA FIREX campaign

Joint CrIS/OMPS retrievals

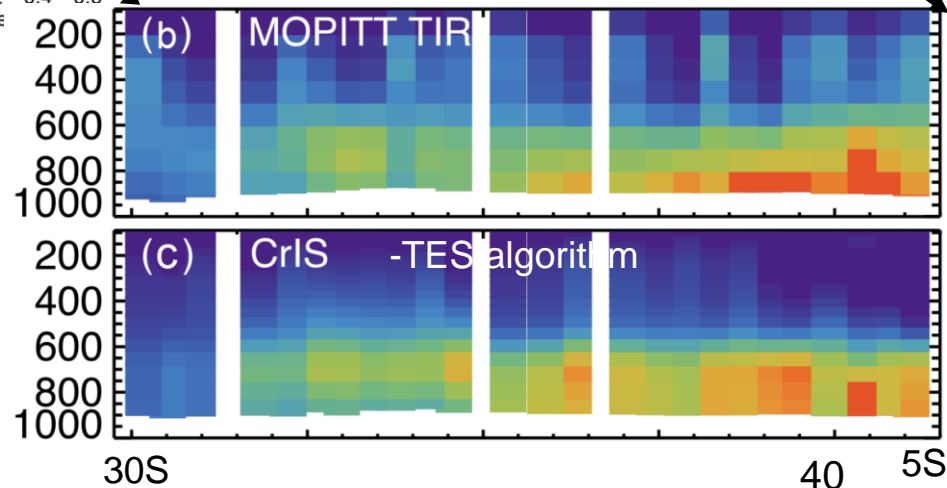
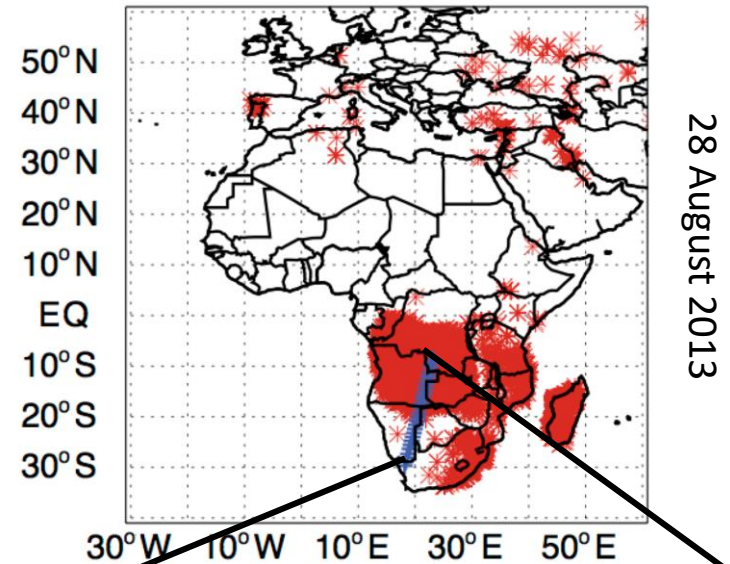
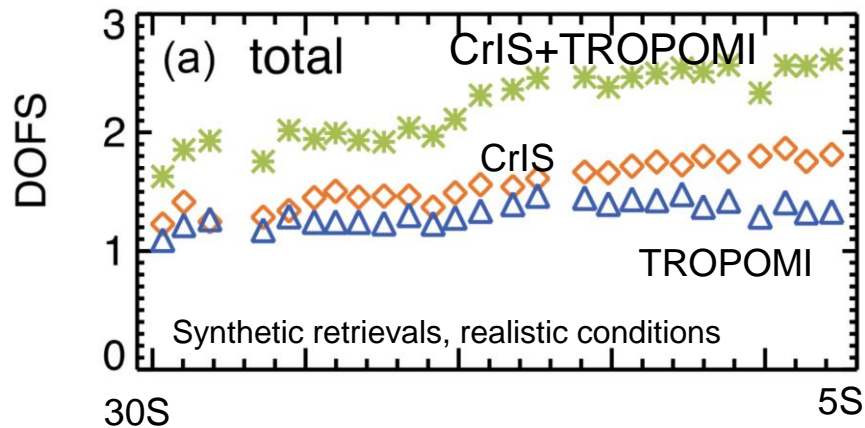
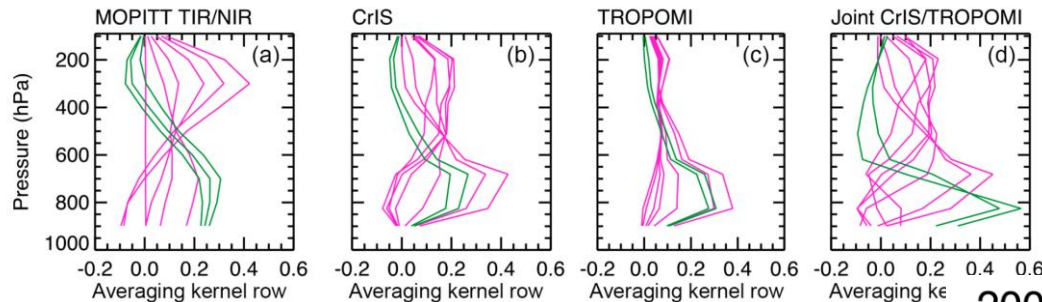


- MUSES has been applied to joint CrIS/OMPS ozone retrievals over Africa on October 21, 2013.
- The elevated ozone concentrations between 2 - 20° S are associated with biomass burning.
- Joint CrIS/OMPS O₃ and CrIS CO retrievals using MUSES will support the NOAA FIREX flight campaign (Fire Influence on Regional and global Environments Experiment) – an intensive study of the impacts of western North America fires on climate and air quality.

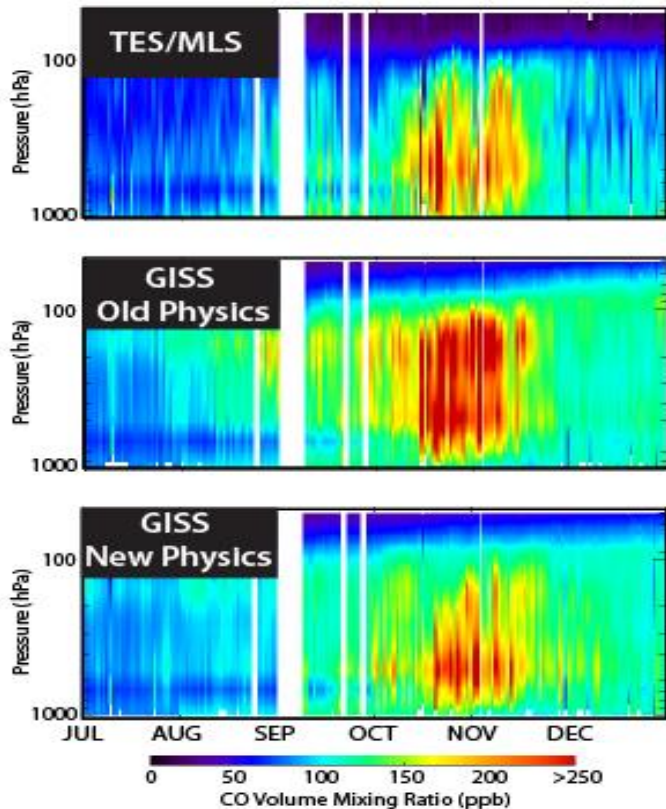
Multispectral CO from CrIS and TROPOMI

No planned follow-on to MOPITT's TIR+NIR CO measurements

Fu et al, AMT (2016): Combining CrIS data with the Sentinel 5p TROPOMI near IR data would have comparable to vertical sensitivity of MOPITT but with daily coverage.



Constraint on model convective parameterizations from TES/MLS CO retrievals



Field, R. D. et al., J. Geophys. Res., 2015.

Measured and modeled CO over Indonesia during a large biomass burning event in Jul-Dec 2006. Adjustments made to the GISS model's convective parameterization provide better agreement with the observations.

Convective parameterizations represent a major uncertainty in climate models, and their accuracy can be very difficult to assess.

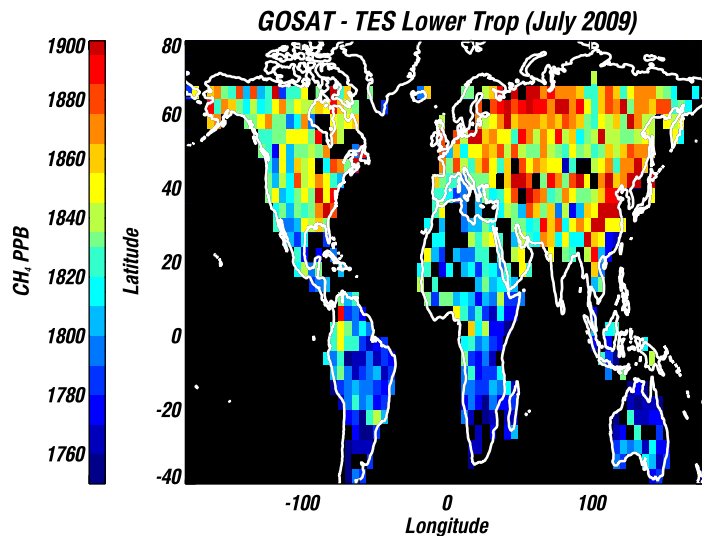
New joint TES/MLS CO retrievals provide 50% higher vertical resolution than TES alone.

These CO profiles have been used to evaluate the composition impacts of changes to the GISS model convective parameterization that were implemented to generate a Madden-Julian Oscillation.

The new physics suppress deep convection when there is low humidity, reducing vertical transport of CO to the upper troposphere.

This study demonstrates the potential for using vertically-resolved composition measurements to better understand and constrain convective processes.

Combining Measurements Reveals Lower Tropospheric Methane Concentrations



Worden, J. R. et al., *Atmos. Meas. Tech.*, 2015.

New data directly show methane from Siberian and N. European wetlands during summer. Tropical fluxes are low because it is the dry season. Large concentrations over E. USA and China are likely due to anthropogenic sources.

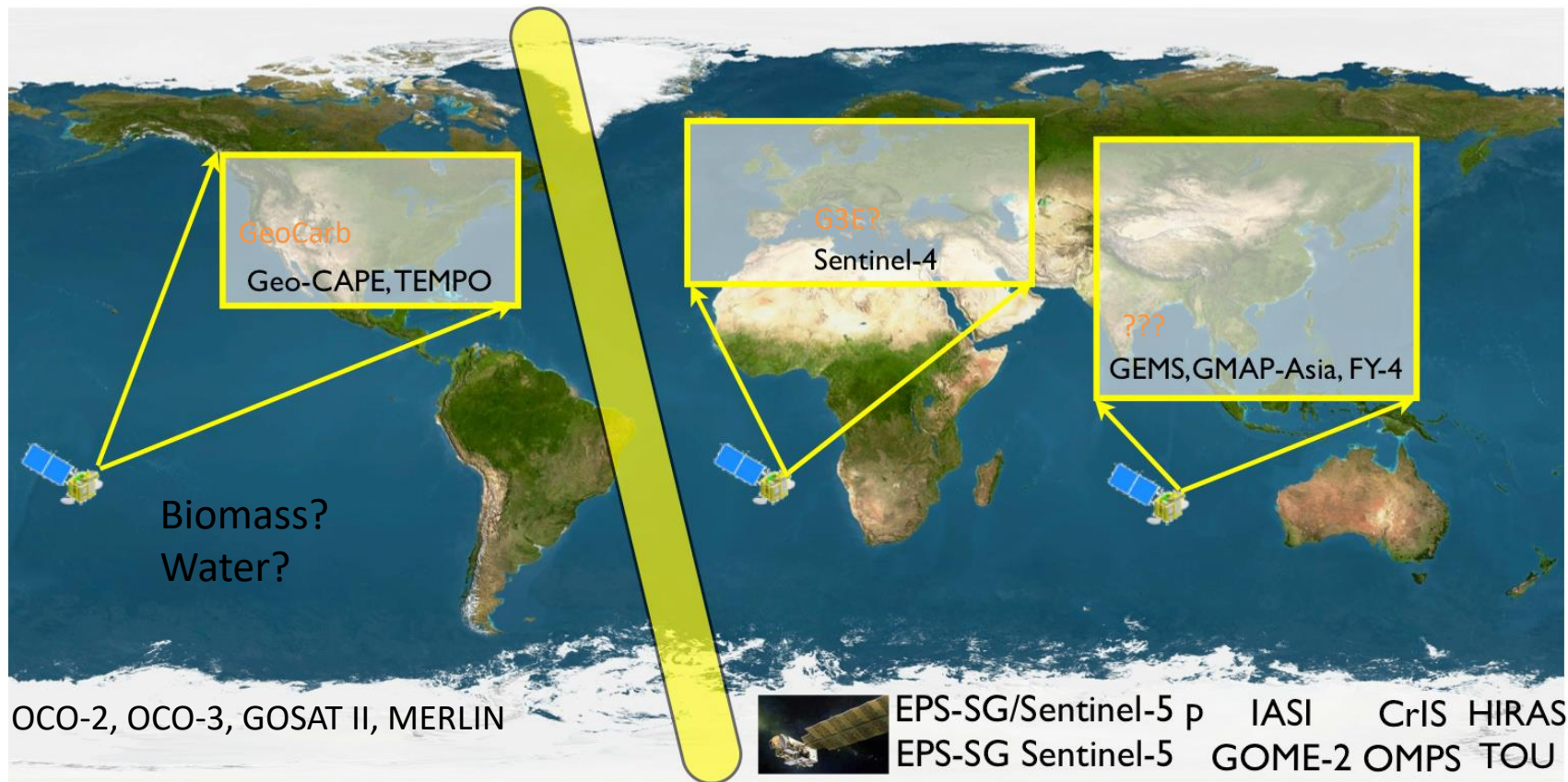
Worden et al. combine Aura TES (IR) CH₄ with GOSAT (Near-IR) CH₄ measurements to quantify lower tropospheric methane.

These data provide an unprecedented view of methane directly over source regions.

The technique for quantifying near-surface methane can be applied more broadly to CH₄ measurements from TROPOMI, GOSAT-2, CrIS, IASI, and AIRS to greatly improve our understanding of methane sources

Toward an Air Quality-Carbon-Climate Constellation

Bowman et al, Atm.Env. 2013



- LEO:
 - IASI+GOME-2, AIRS+OMI, CrIS+OMPS could provide UV+IR ozone products for more than a decade.
 - Combined UV+IR ozone products from GEO-UVN and GEO-TIR aboard Sentinel 4 (Ingmann *et al*, 2012 Atm. Env.)
 - Sentinel 5p (TROPOMI) will provide column CO and CH₄.
 - OCO-2+AIRS, GOSAT II (IR+NIR) could provide vertical discrimination.
- GEO
 - TEMPO, Sentinel-4, and GEMS, would provide high spatio-temporal air quality information.
 - GeoCarb and G3E could provide geo-carbon information.

Summary/final thoughts

- **Past decade has seen dramatic redistributions in sources of pollution**
- The trajectory of atmospheric composition sources/sinks and its impact on the Earth System is both highly uncertain and critically important for climate and environmental health mitigation.
- We **will** have the nadir sounder measurements to 2031 and beyond
 - Provides exciting opportunities to develop and analyze long-term records
- Long-term records of **multiple trace gases** are needed:
 - To observe changes in composition over decadal timescales
 - To disentangle seasonal and interannual variability from trends
 - To evaluate and improve representation of key processes in models
 - To observe and interpret the co-evolution of composition and climate
- **Sensitivity diagnostics** and **well-characterized errors** are key to effective scientific utilization of the data

Back-up slides